Gravitational waves from QCD-triggered conformal symmetry breaking

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Overview

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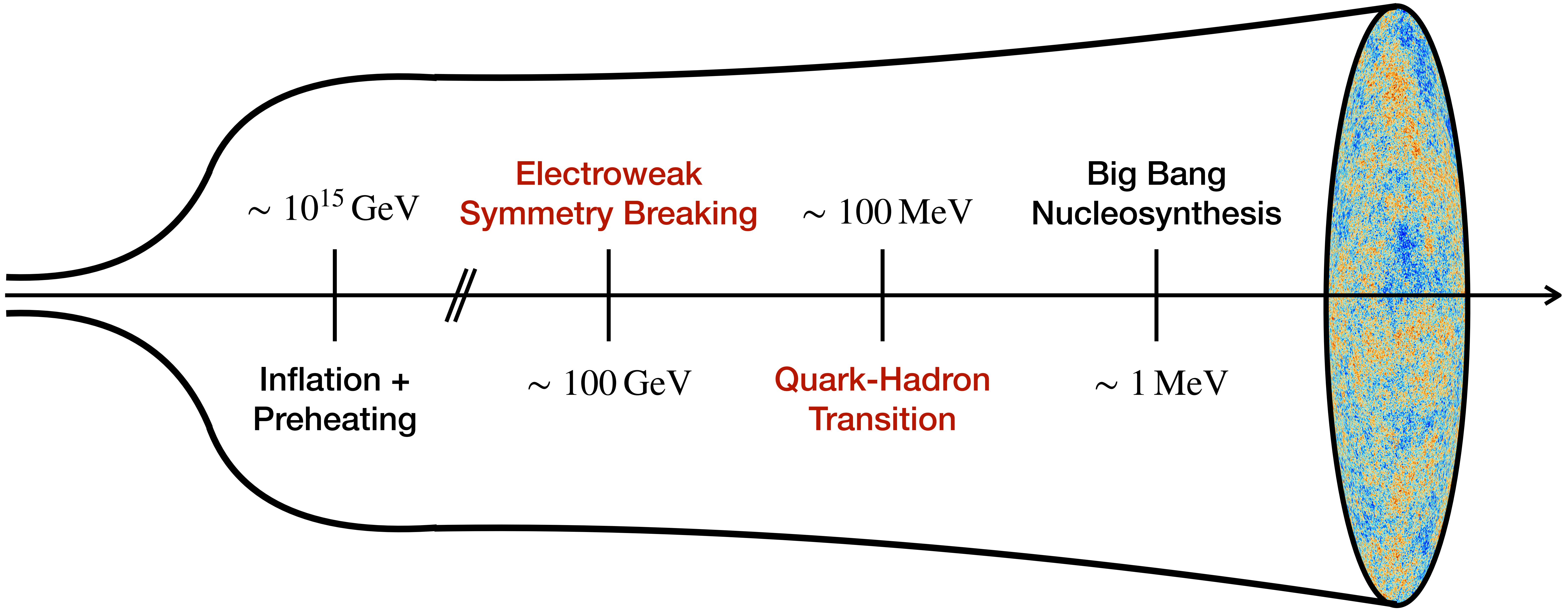
Standard Model (SM): QCD + electroweak (EW) transition separated

Crossover transitions[1]: no gravitational wave (GW) emission

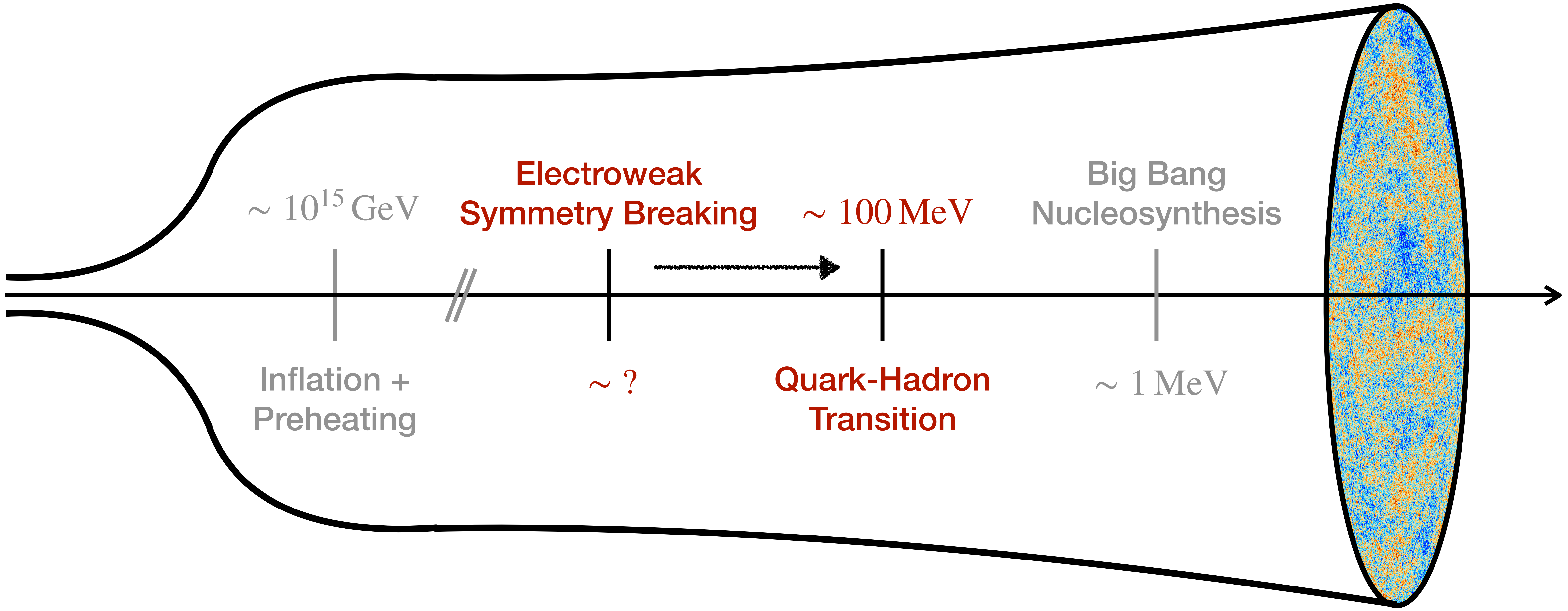


[1]Kajantie et al. [1996]; Aoki et al. [2006]

Overview

Scale-invariant SM extensions: EW transition delayed[2]

Possible outcome: strong first-order QCD transition



[2]Iso, Serpico, Shimada [2017]; von Harling, Servant [2017]

1. The Supercooled Universe

Classically Conformal (CC) Models

- Two main principles:

  1. Extend SM by additional gauge symmetry with scalar field Φ (e.g. $U(1)_{B-L}$)

  2. Impose scale invariance at tree level[3]

[3] e.g. Iso, Okada, Orikasa [2009]

Classically Conformal (CC) Models

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  2. Impose scale invariance at tree level[3]

$$V(H,\Phi) = \lambda_\Phi \Phi^4 + \lambda H^4 - \lambda_p \Phi^2 H^2$$

Higgs mass term replaced by portal coupling: $-\mu^2 H^2 \rightarrow -\lambda_p \Phi^2 H^2$

[3]e.g. Iso, Okada, Orikasa [2009]

Symmetry Breaking Pattern

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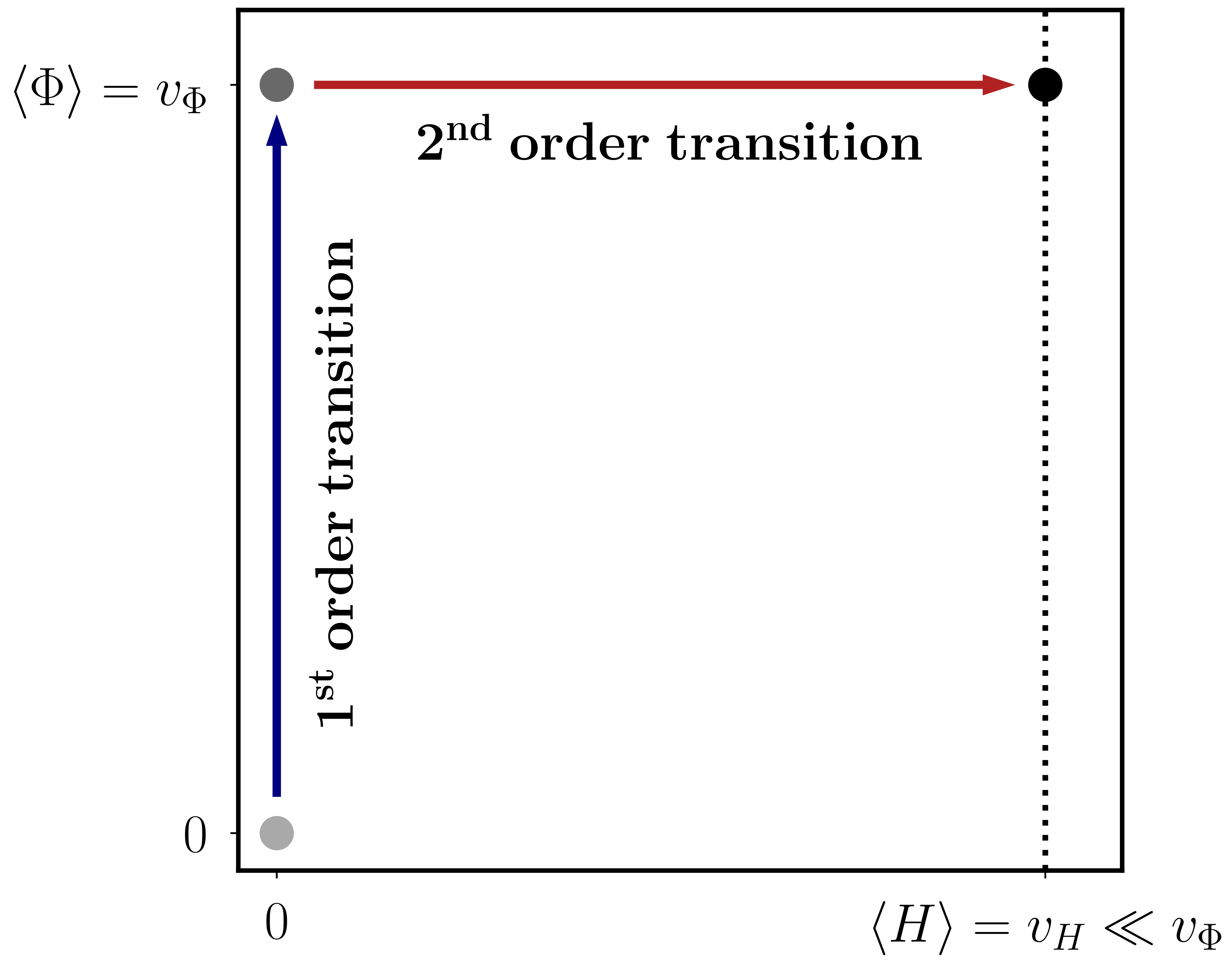
Conformal symmetry broken radiatively

$$\langle \Phi \rangle = v_\Phi \quad \rightarrow \quad \mu_H^2 = \lambda_p v_\Phi^2$$

Higgs mass generated dynamically



Conformal Symmetry Breaking

Flat potential around origin

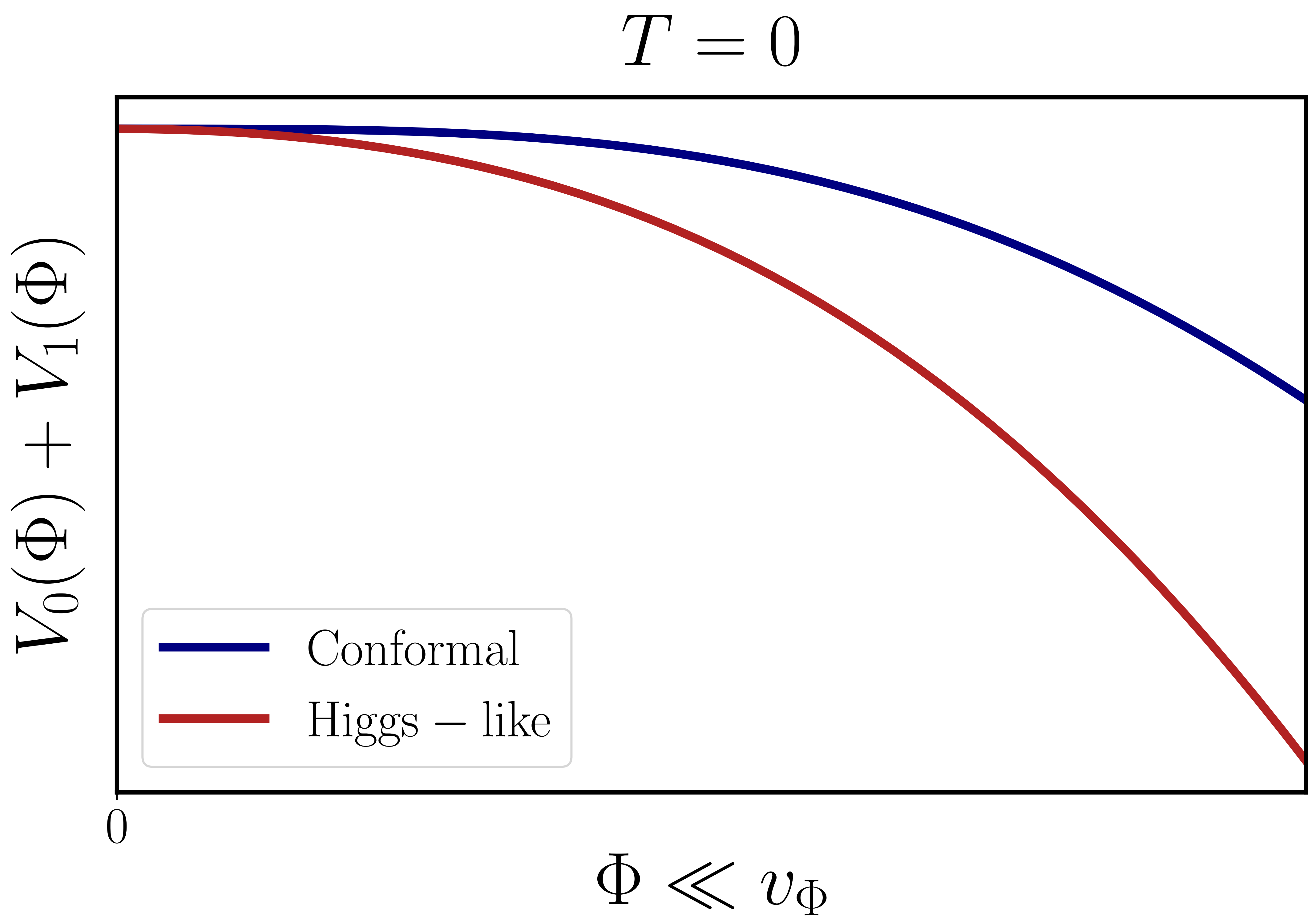
↓

Thermal barrier remains until $T \to 0$

↓

Universe trapped in false vacuum

Possible Supercooling[4] to $T_p \ll T_{\mathrm{EW}}$



[4] e.g. Marzo et al. [2018]; Ellis et al. [2020]; Kierkla et al. [2022]

Supercooling and the QCD Transition

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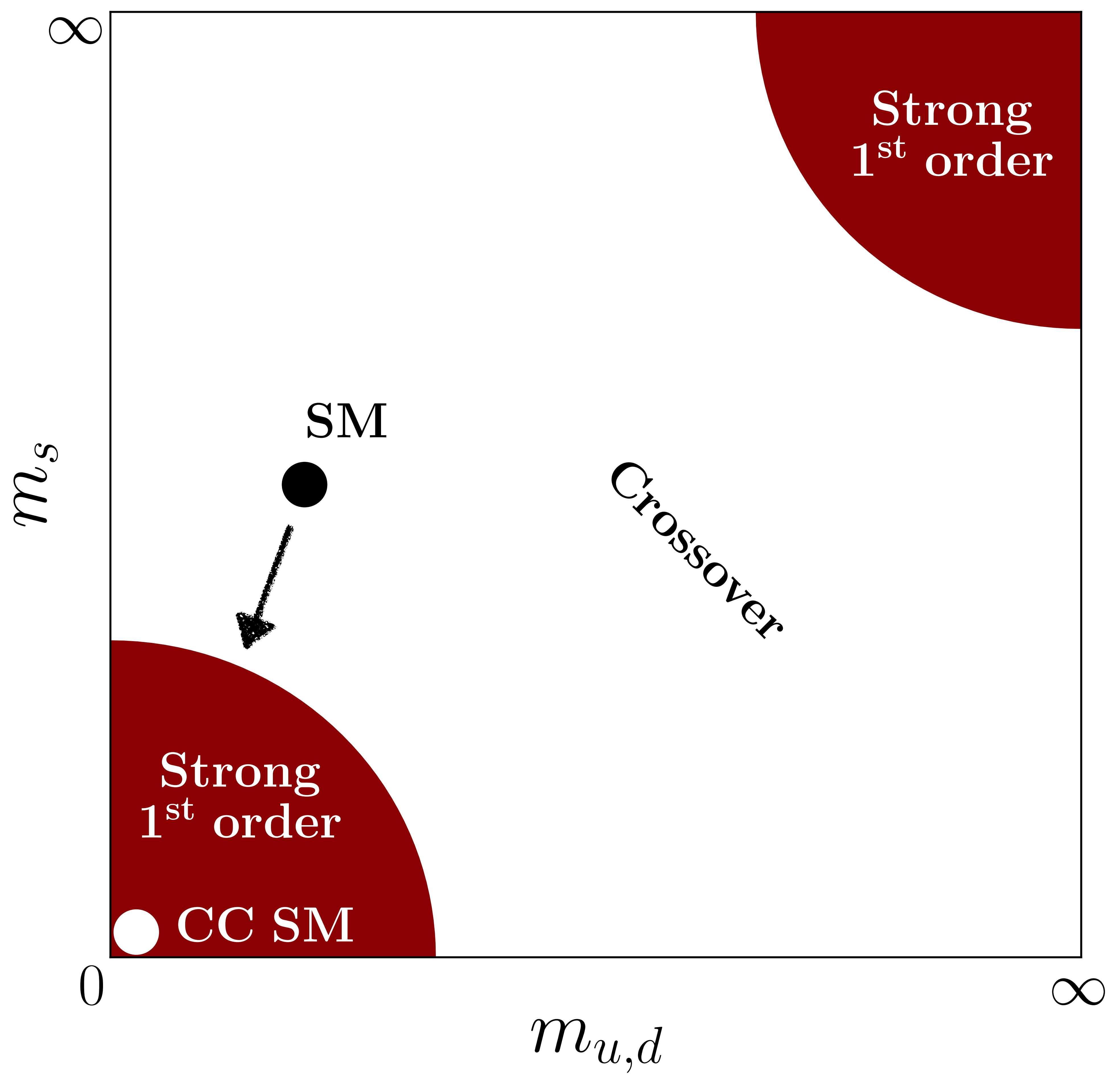
EWPT can be supercooled to QCD scale

Quarks remain massless



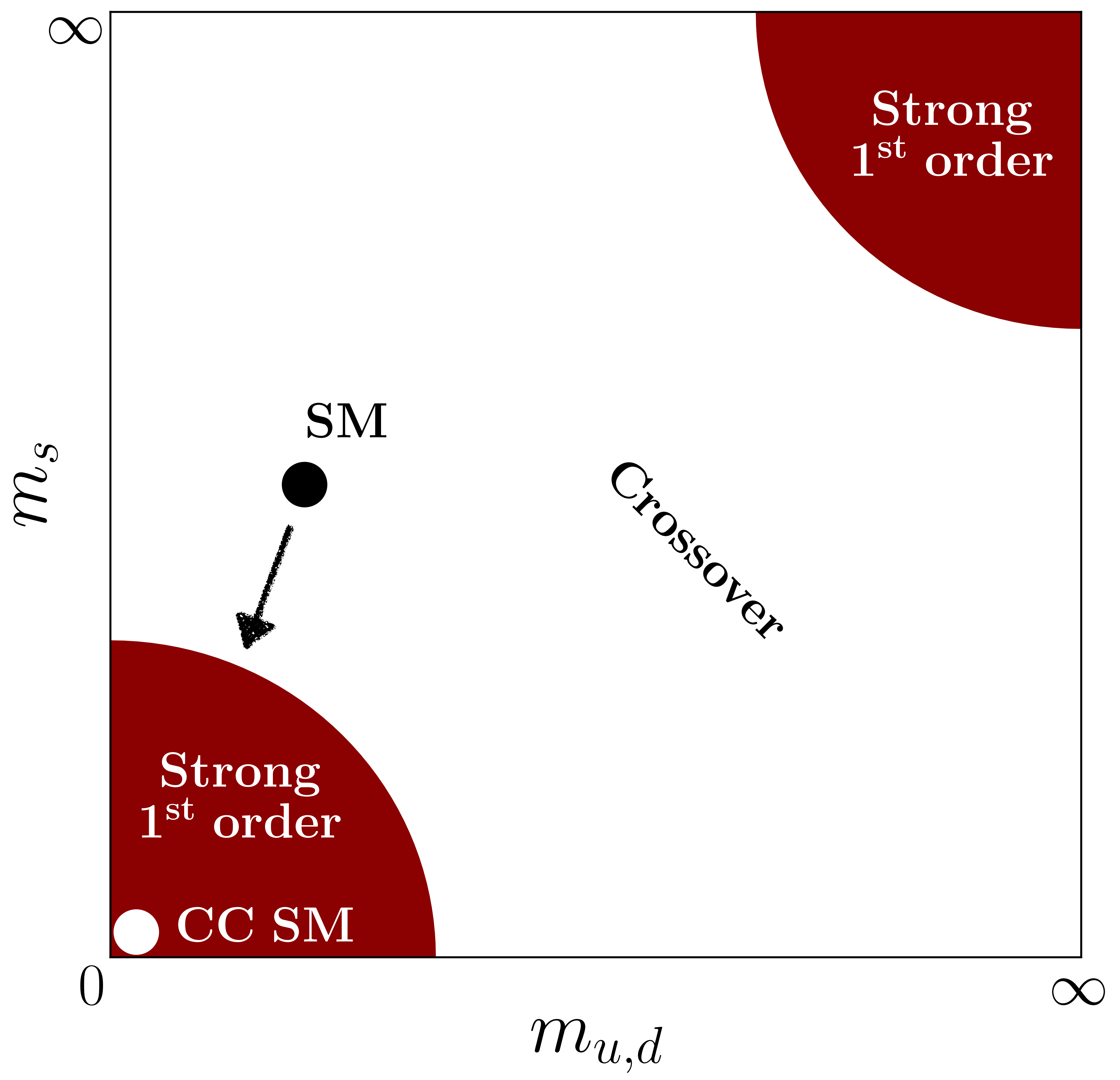
Supercooling and the QCD Transition

EWPT can be supercooled to QCD scale

Quarks remain massless

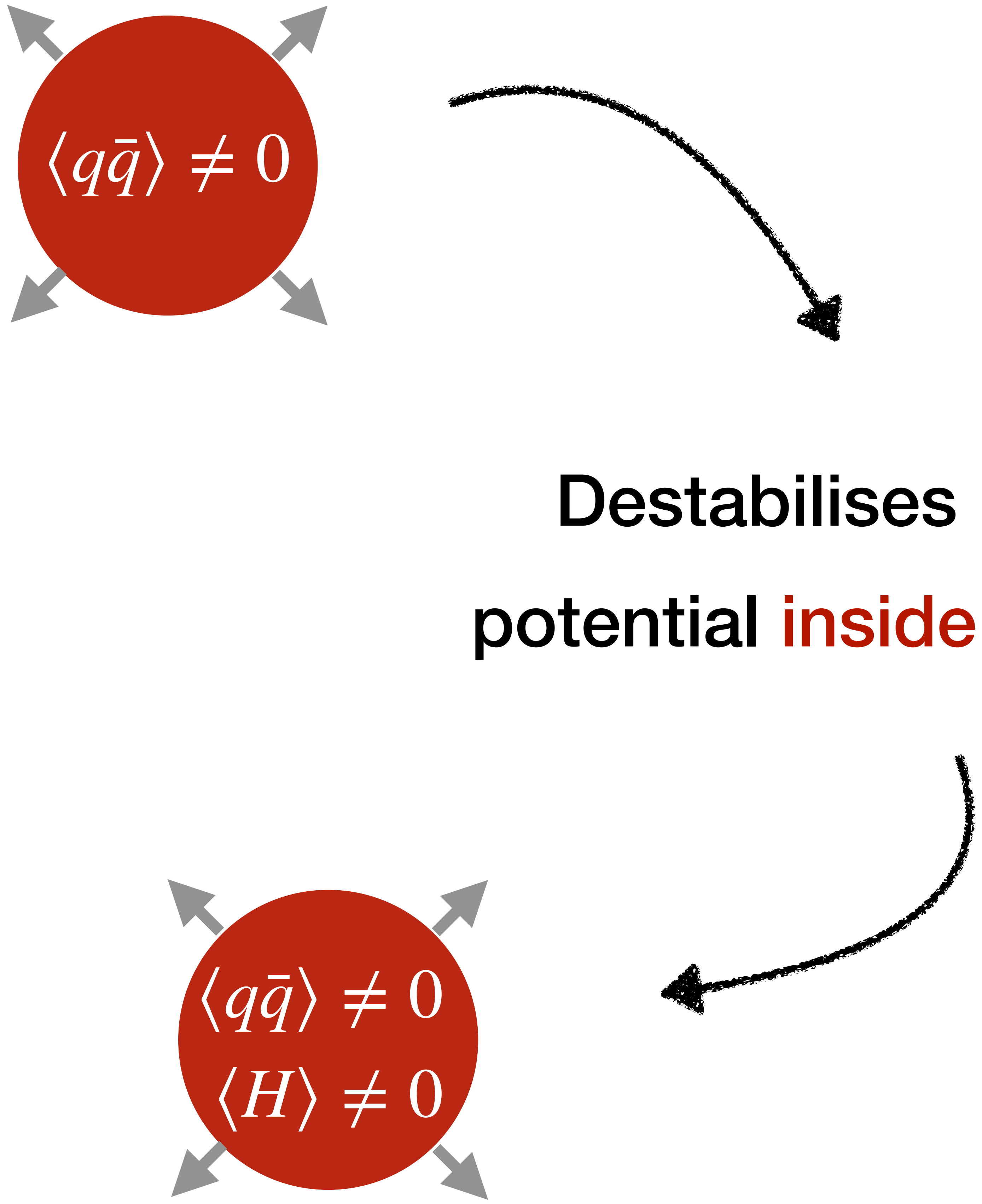
First-order chiral quark-hadron transition[5]

$$\langle q\bar{q}\rangle \neq 0$$



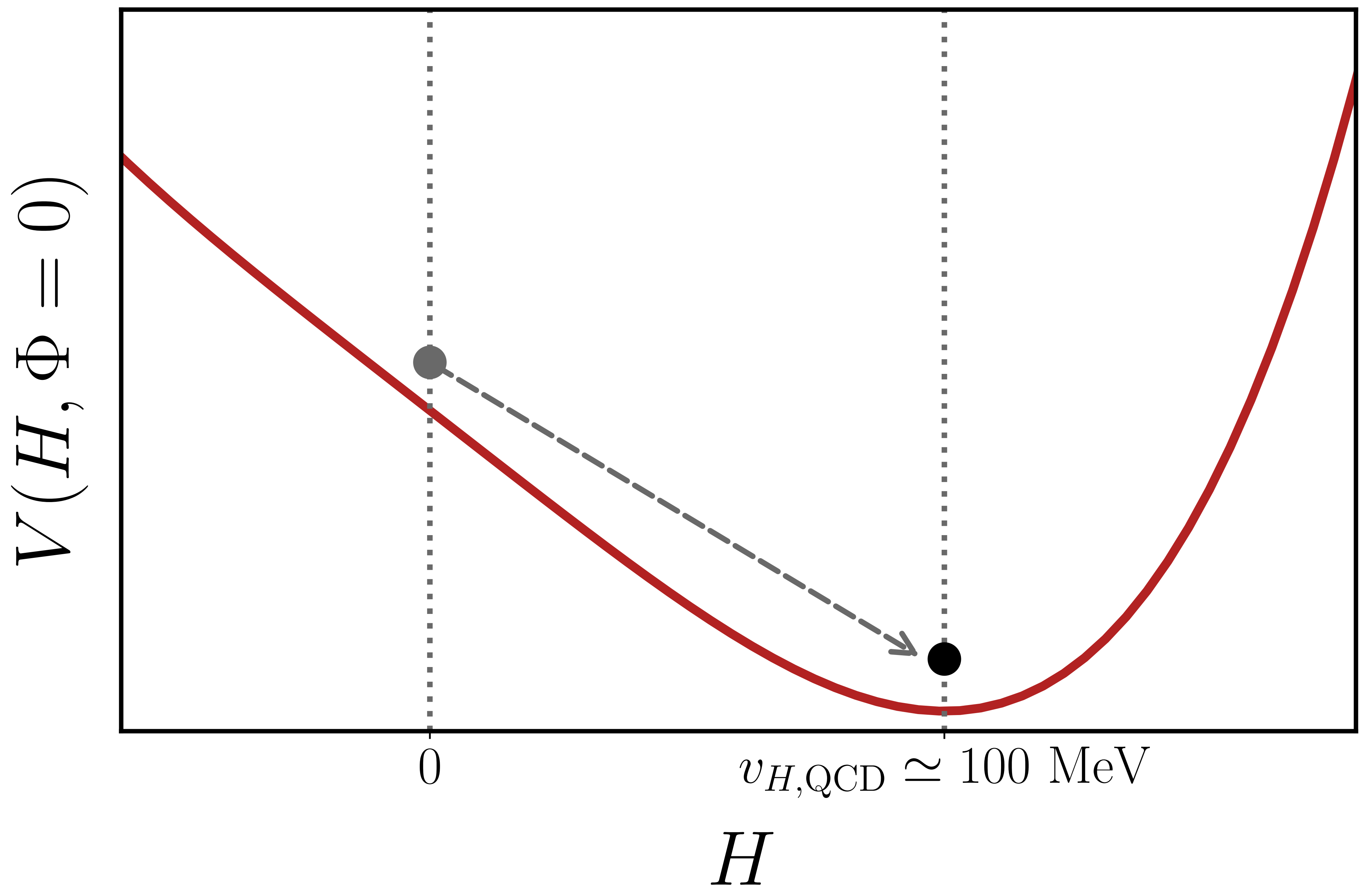
[5]Pisarski, Wilczek [1984]; Brown, Butler, Chen et al. [1990]

Combined QCD - EW Phase Transition



Destabilises Higgs potential inside bubble[6]

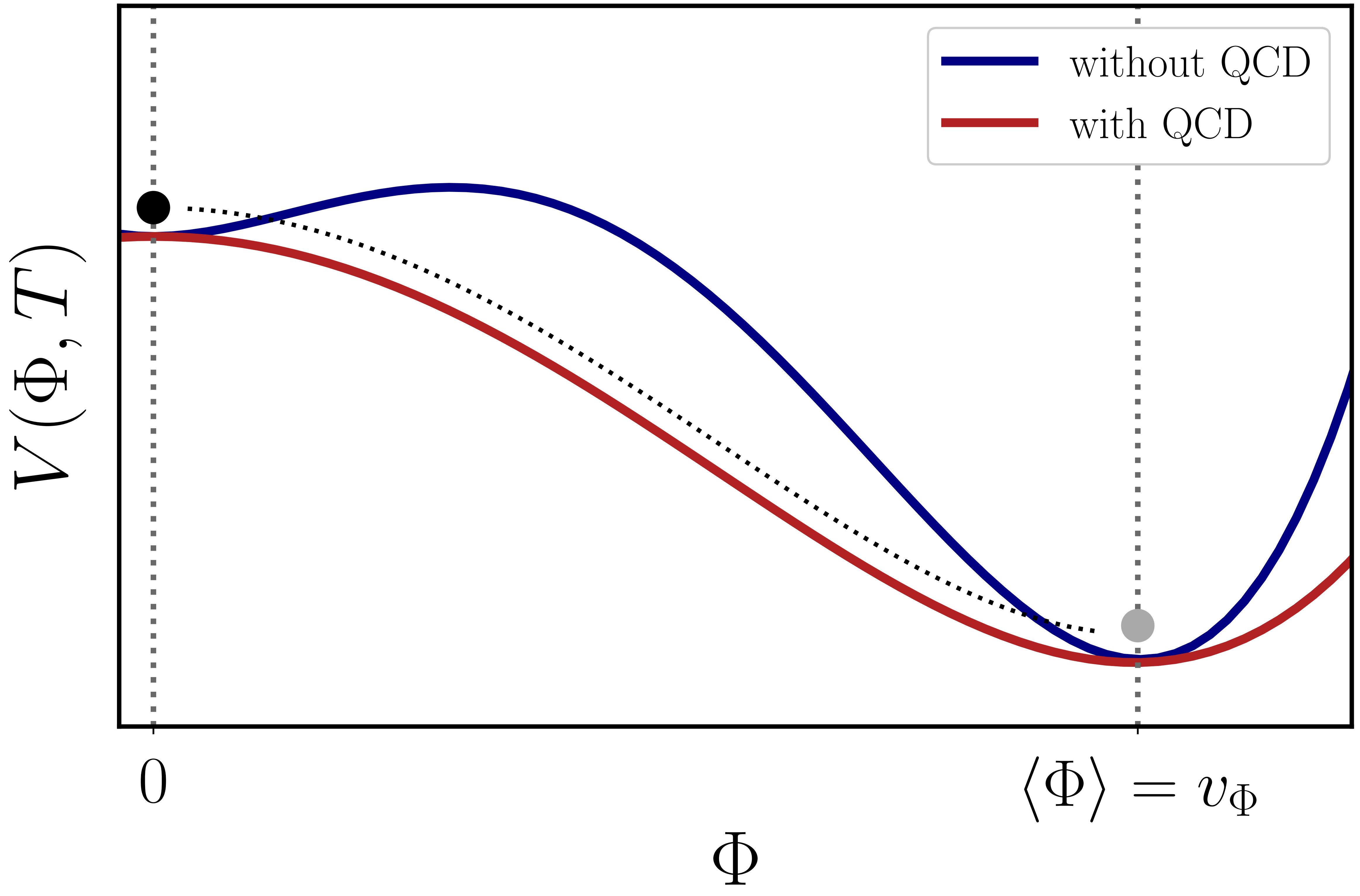
$$V(H) = \lambda_H H^4 + y_q \langle q\bar{q}\rangle H$$



[6] Iso, Serpico, Shimada [2017]; von Harling, Servant [2017]

Supercool Exit

QCD-triggered EWSB breaks scale invariance $V_{\mathrm{QCD}}(\Phi) = \lambda_p \langle H \rangle^2_{\mathrm{QCD}} \Phi^2$



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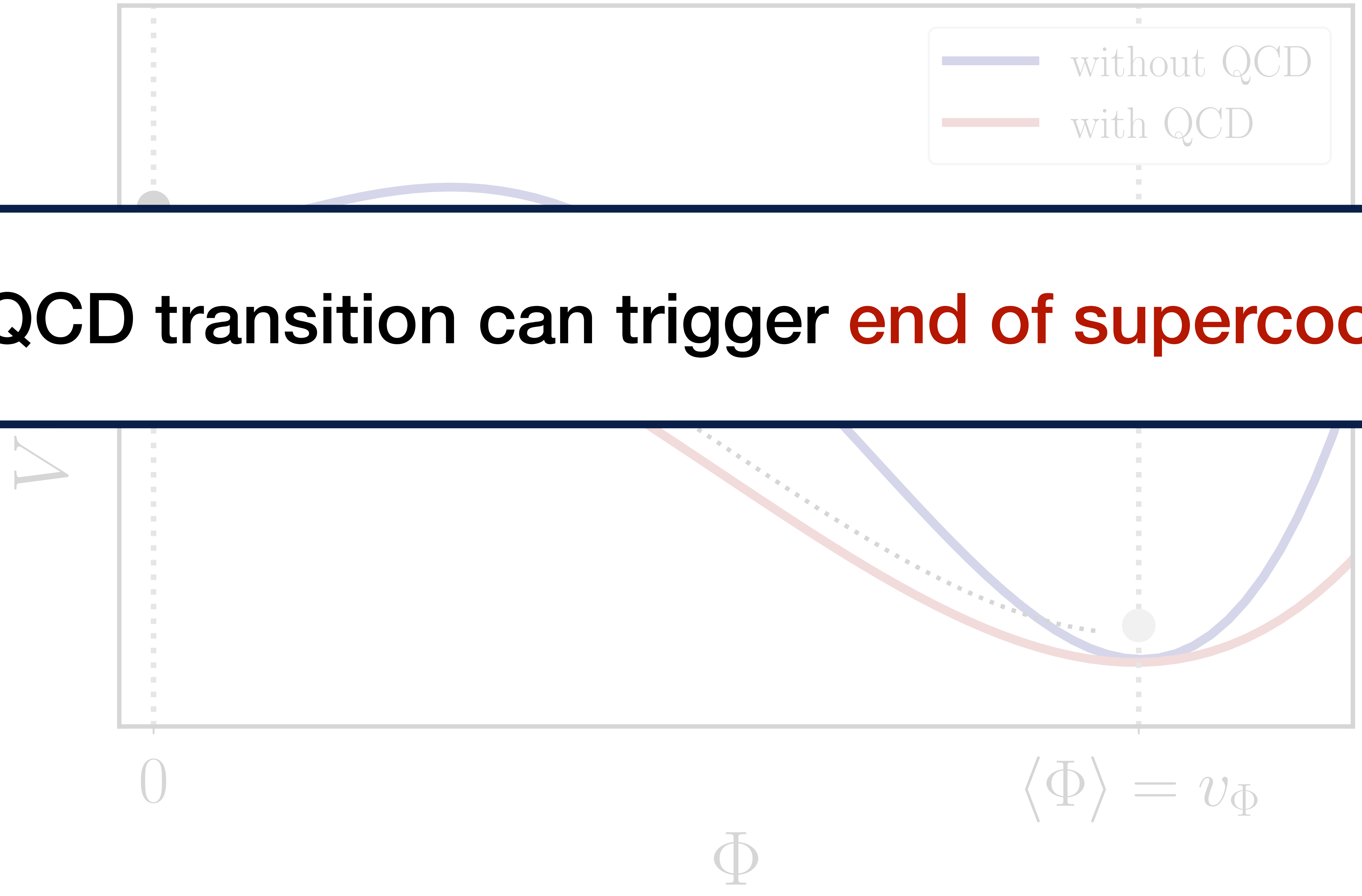
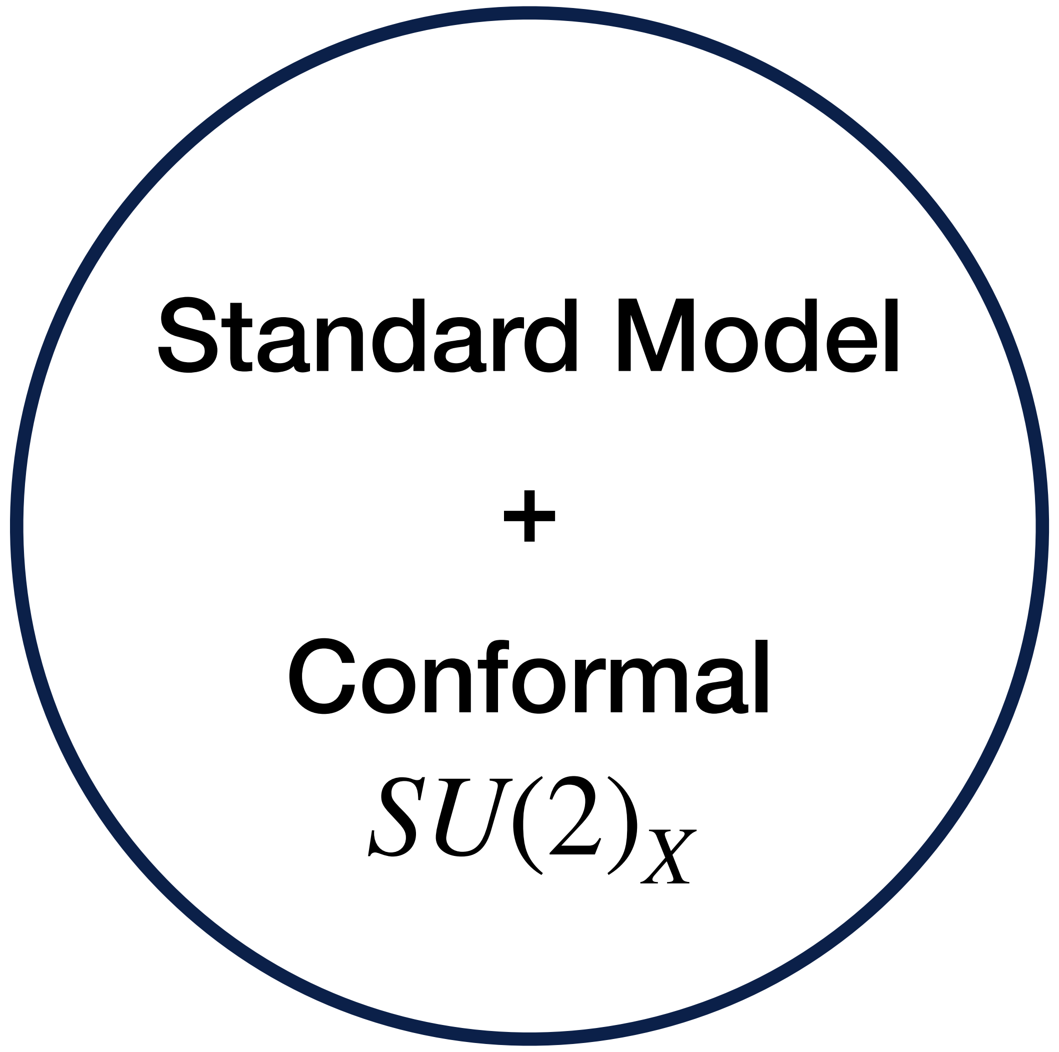


QCD transition can trigger end of supercooling

Viable Parameter Space

Example:



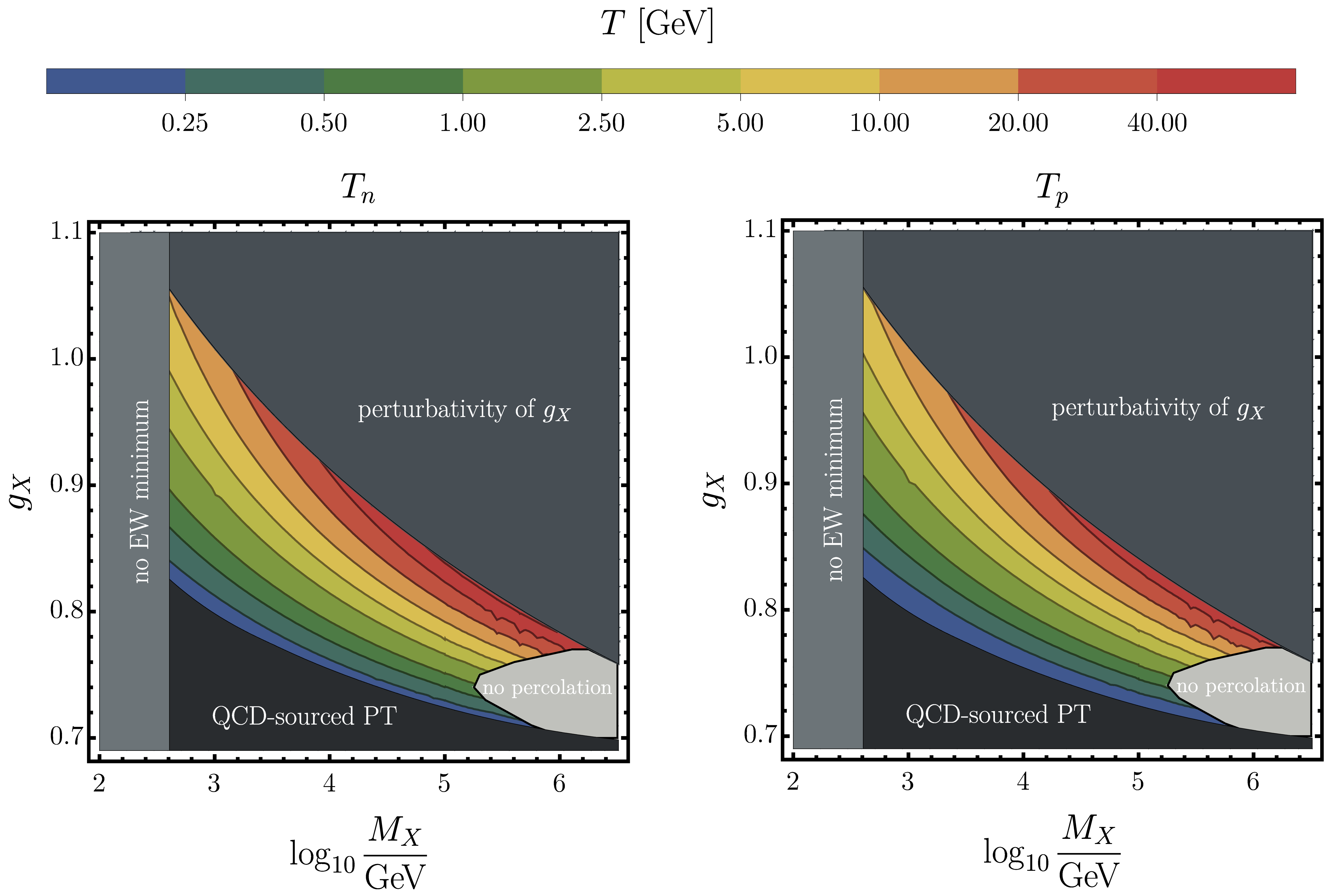
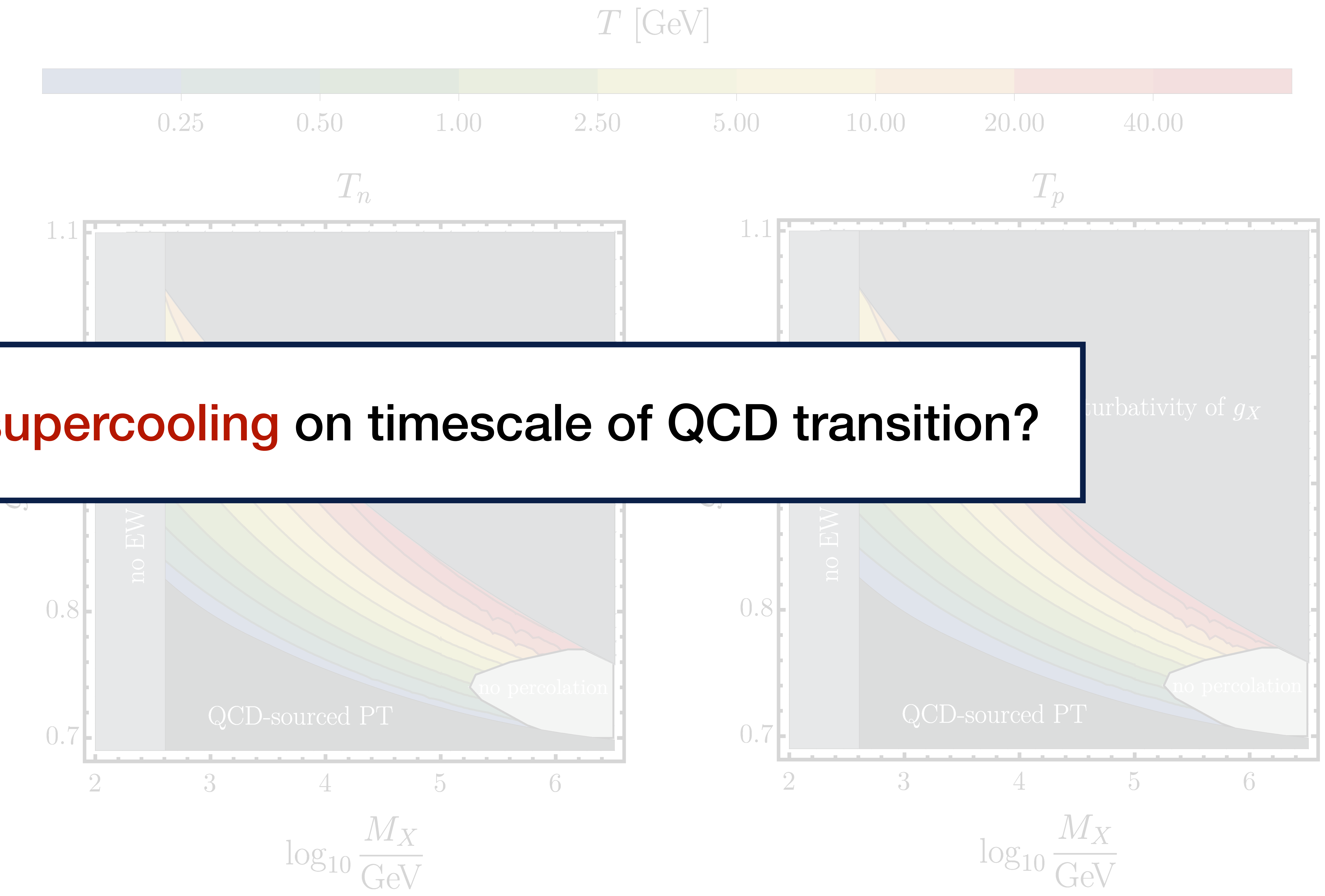


Figure: Kierkla, Karam, Świeżewska [2022]

Viable Parameter Space

Example:

Standard
+
Conformal
$SU(2)_X$



Impact of supercooling on timescale of QCD transition?

Figure: Kierkla, Karam, Świeżewska [2022]

Viable Parameter Space

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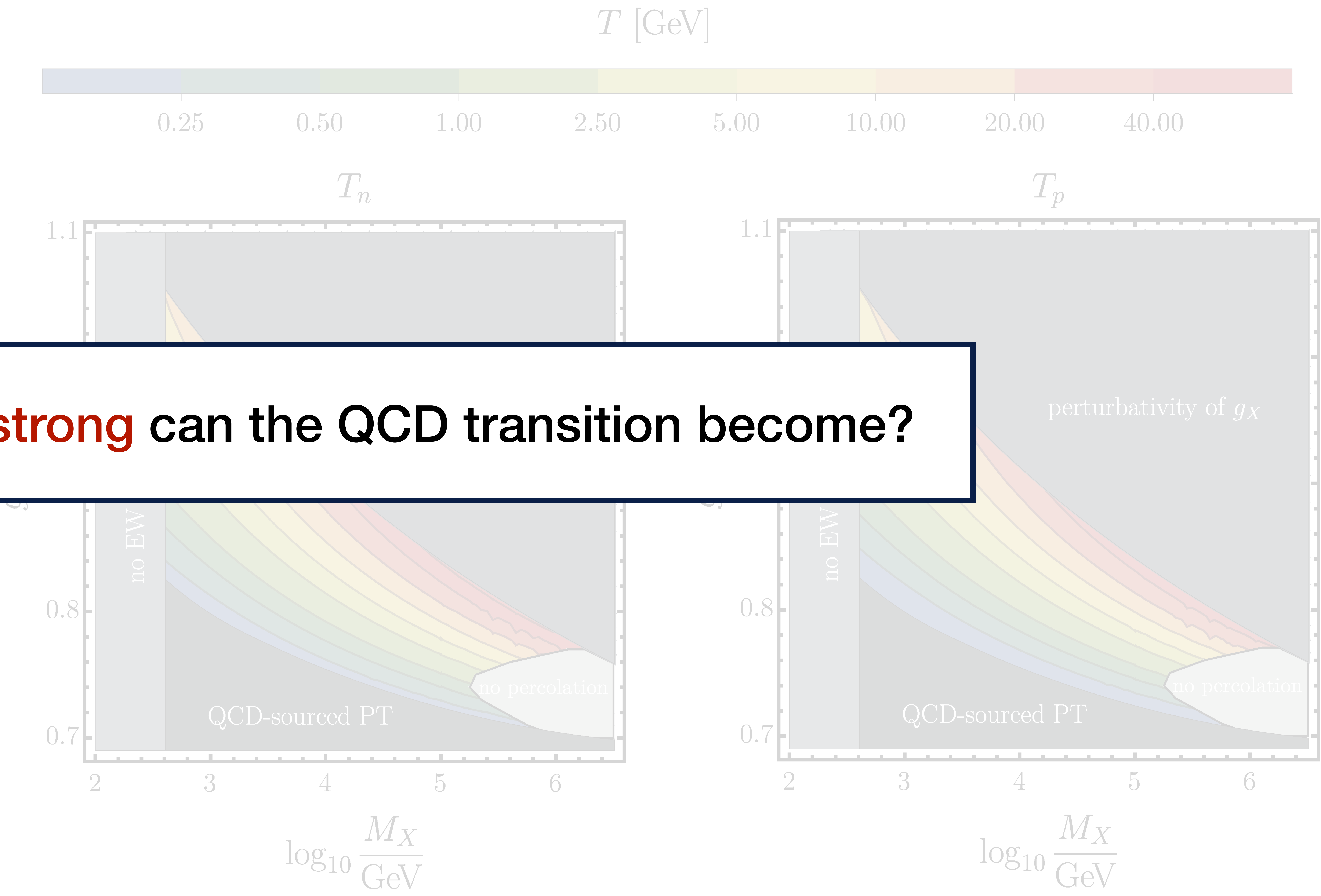
Example:

Standard Model + Conformal $SU(2)_X$

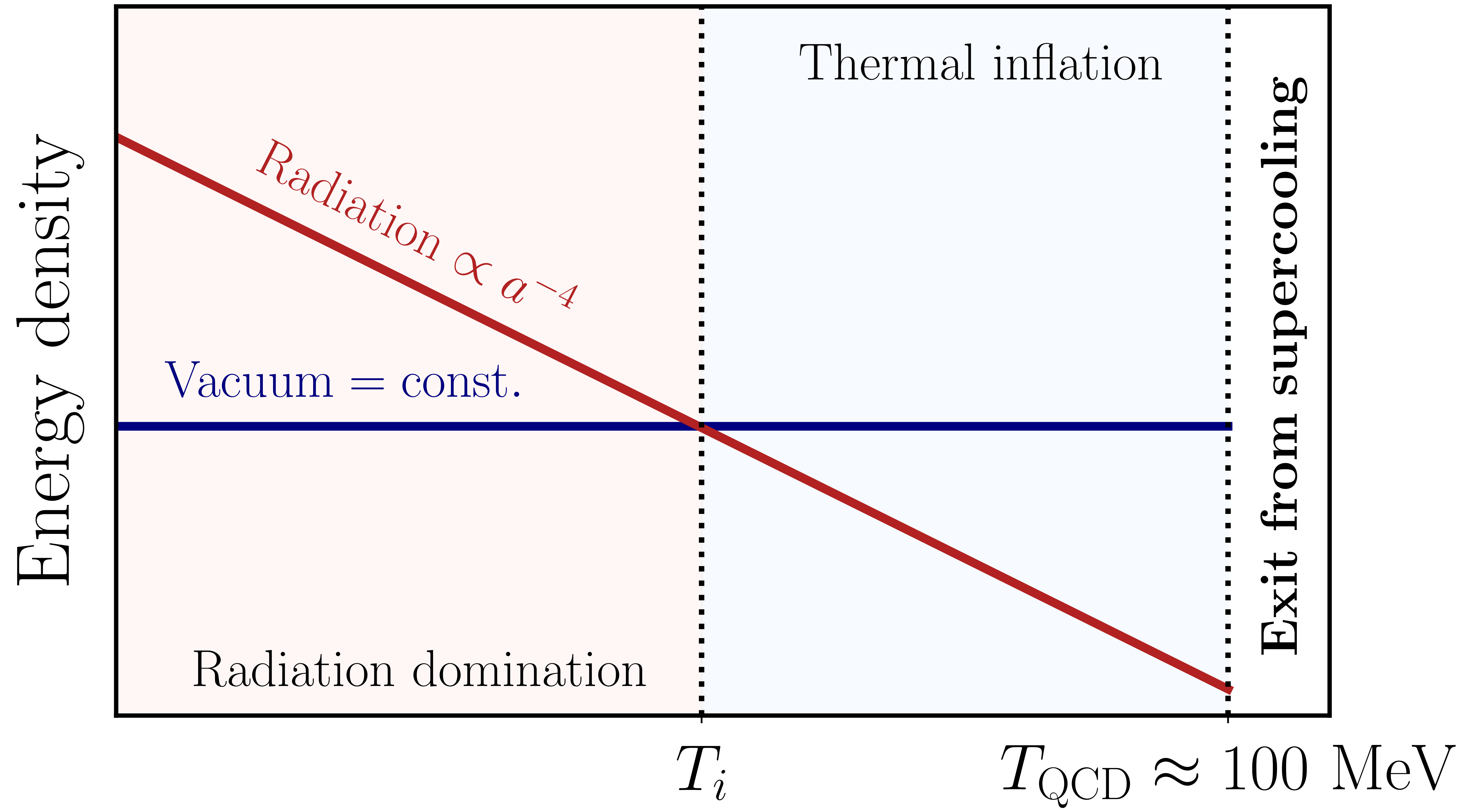


How strong can the QCD transition become?

Figure: Kierkla, Karam, Świeżewska [2022]

2. Supercooled QCD Phase Transition

Our Setup



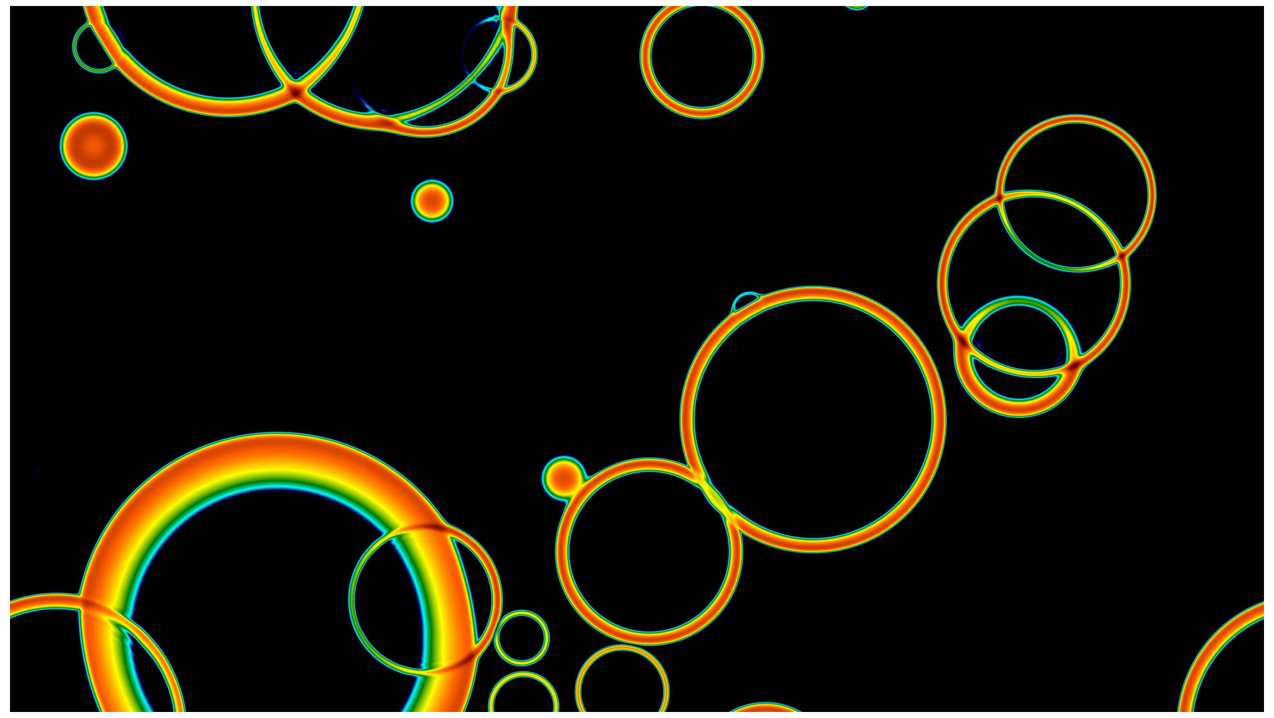
Input: temperature of thermal inflation T_i

$$3M_{\rm Pl}^2 H^2 \simeq \Delta V_{\rm CC\,SM} = \frac{\pi^2}{30} g_\star T_i^4$$

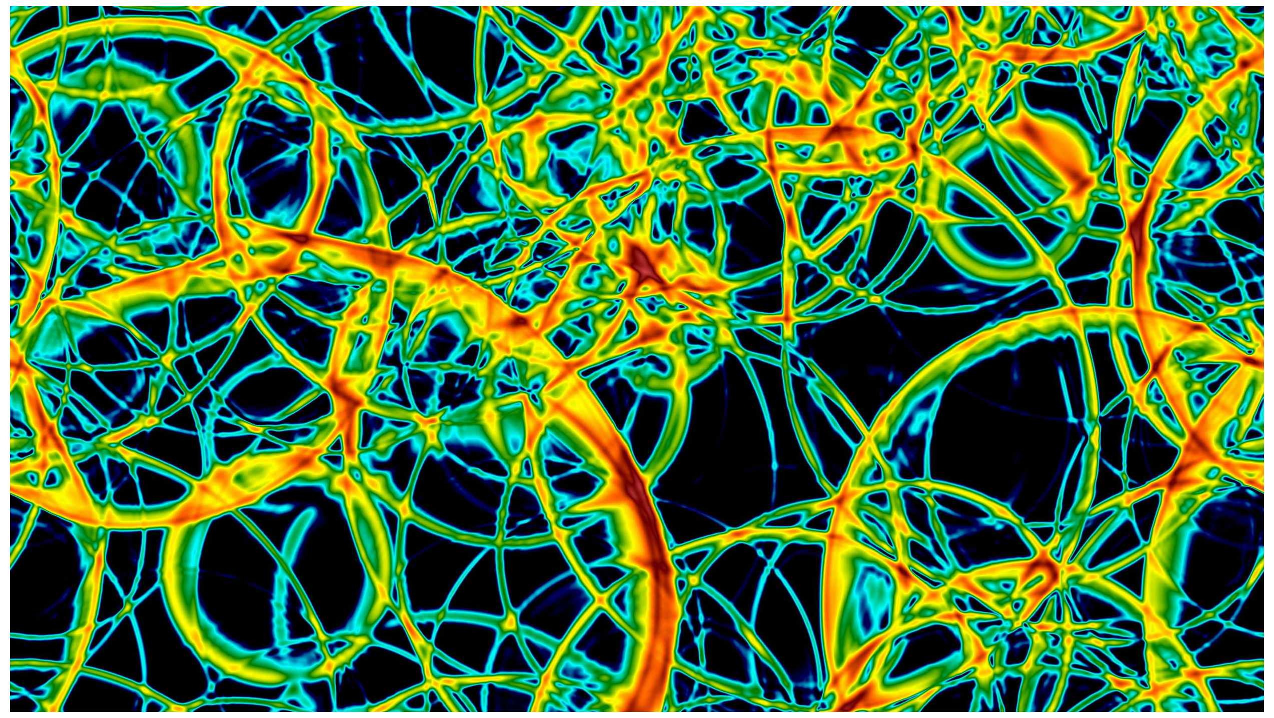
Compute transition dynamics via effective QCD models[7]

[7] For review of effective QCD models see e.g. Fukushima et al. [2017]

Gravitational Waves from First-Order PTs



$$\Omega_{\mathrm{GW}} \propto \frac{\alpha}{1+\alpha} \times \left(\frac{H}{\beta}\right)^2$$



Figures: Weir [2018]

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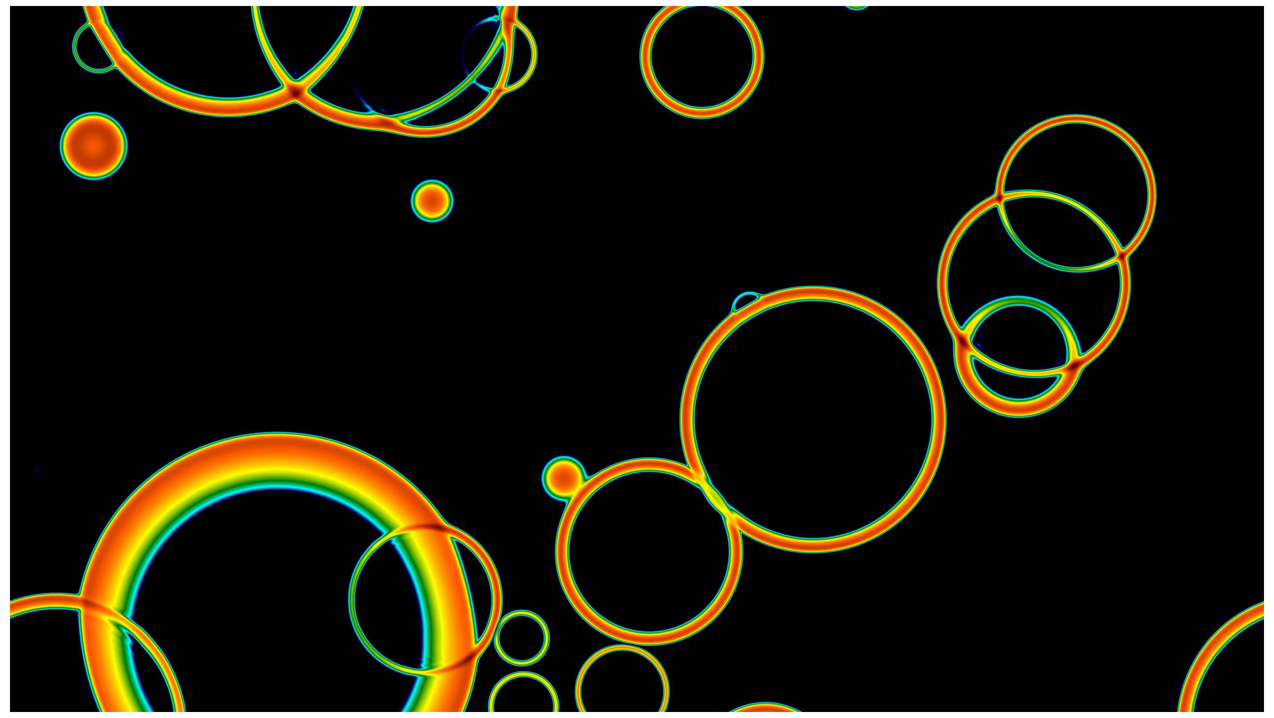

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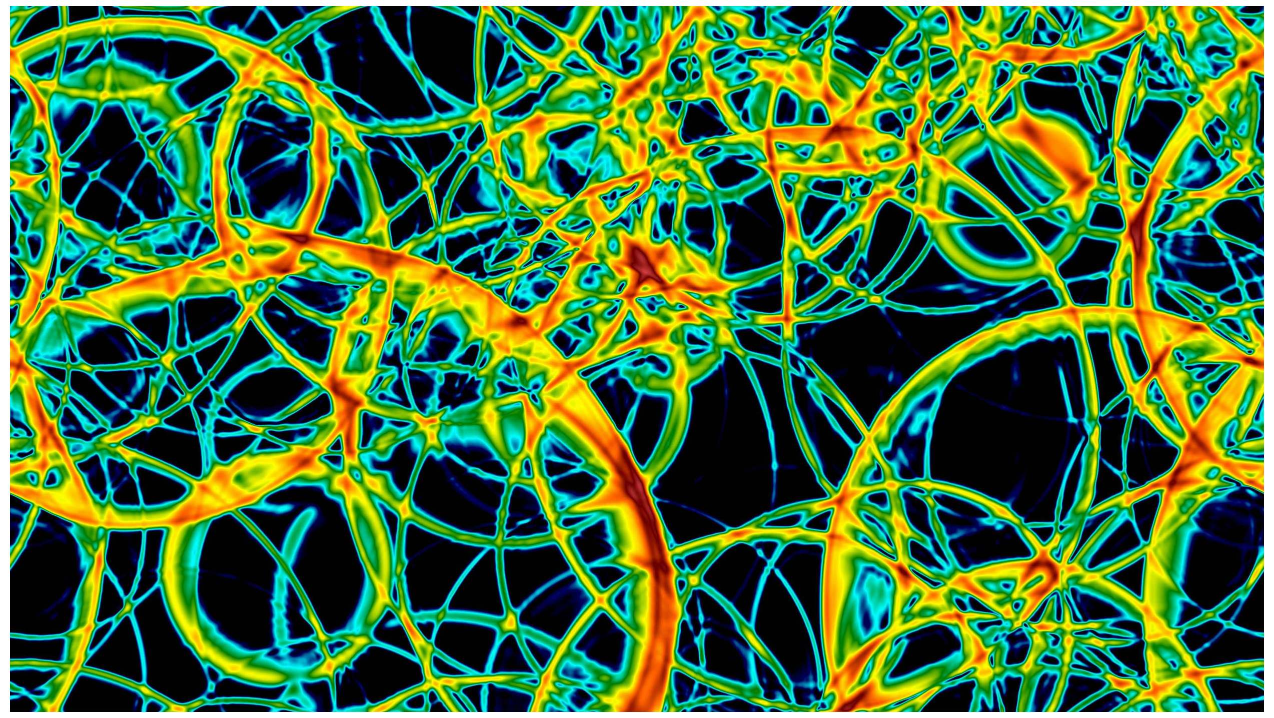

Figures: Weir [2018]

Transition strength α

$$\alpha = \frac{\Delta V(\Phi)}{\rho_{\mathrm{rad}}(T_{\mathrm{QCD}})} \propto \underbrace{\left(\frac{T_i}{T_{\mathrm{QCD}}}\right)^4}_{\text{BSM physics}} \gg 1$$

Gravitational Waves from First-Order PTs

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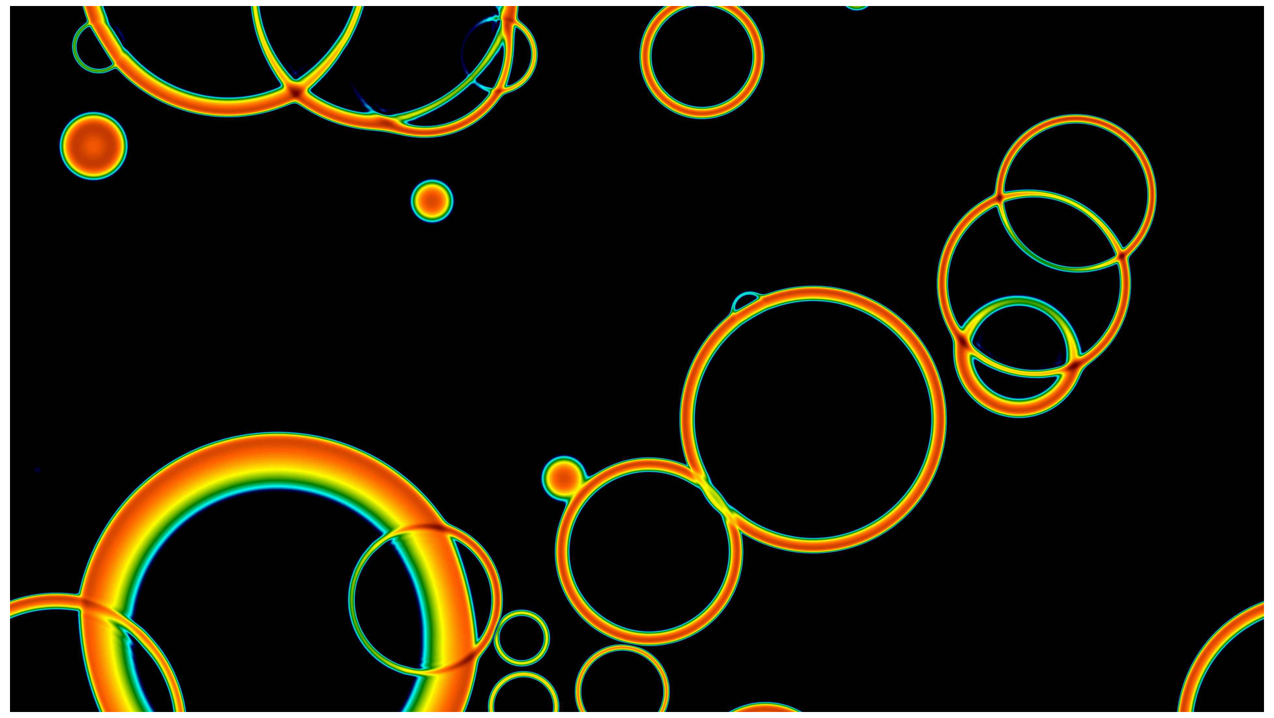

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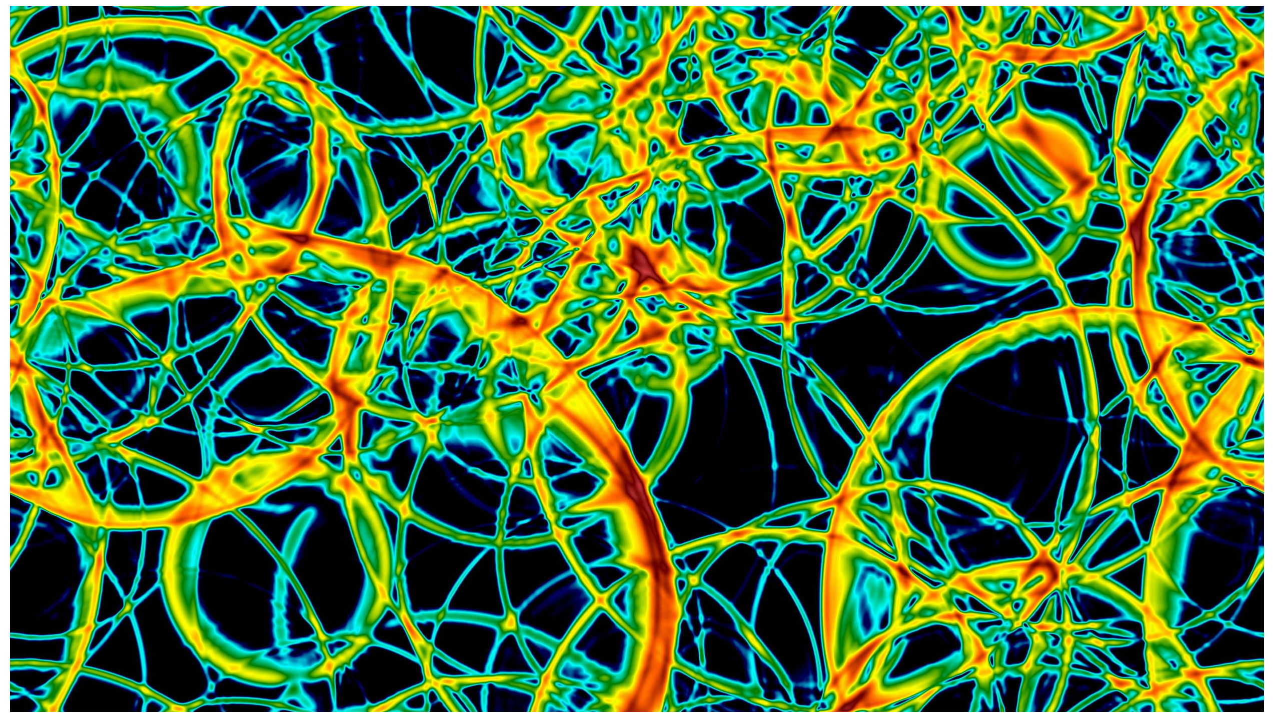

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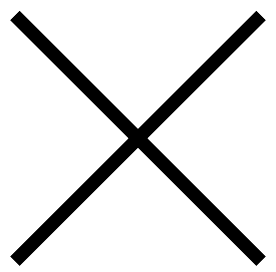
Inverse timescale β

Nucleation of hadronic bubbles

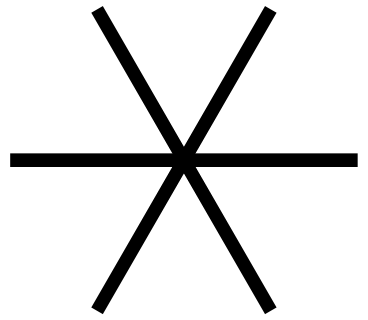
Nambu—Jona-Lasinio (NJL) Model

- Quark-based effective theory[8]

$$\mathscr{L} = \sum_i \bar{q}_i \left(i\partial\!\!\!/ - m_i \right) q_i \quad + \quad \underbrace{\mathscr{L}_{\mathrm{4F}}} \quad + \quad \underbrace{\mathscr{L}_{\mathrm{6F}}}$$



$\sim G$



$\sim G_D$

- Fit model parameters to recover properties of QCD $\longrightarrow$ Take chiral limit $m_i \to 0$

[8]Nambu, Jona-Lasinio [1961]; Klevansky [1996]; Kunihiro [1990]

What about gluons?

Quark confinement $\longrightarrow$ Diverging free energy

What about gluons?

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- Fundamental traced Polyakov loop[9] ℓ

$$\ell(\mathbf{x}) = \frac{1}{N_c}\mathrm{Tr}_c\mathbf{L} = \exp\left(-\beta F_q(r)\right) \;, \quad \text{where} \quad \mathbf{L} = \mathscr{P}\exp\left[ig_s\int_0^{\beta=1/T} d\tau\, \underbrace{A_4(\mathbf{x},\tau)}_{iA_0}\right]$$

Quark confinement $\longrightarrow$ Diverging free energy

[9]Fukushima [2004]; Fukushima, Skokov [2017]

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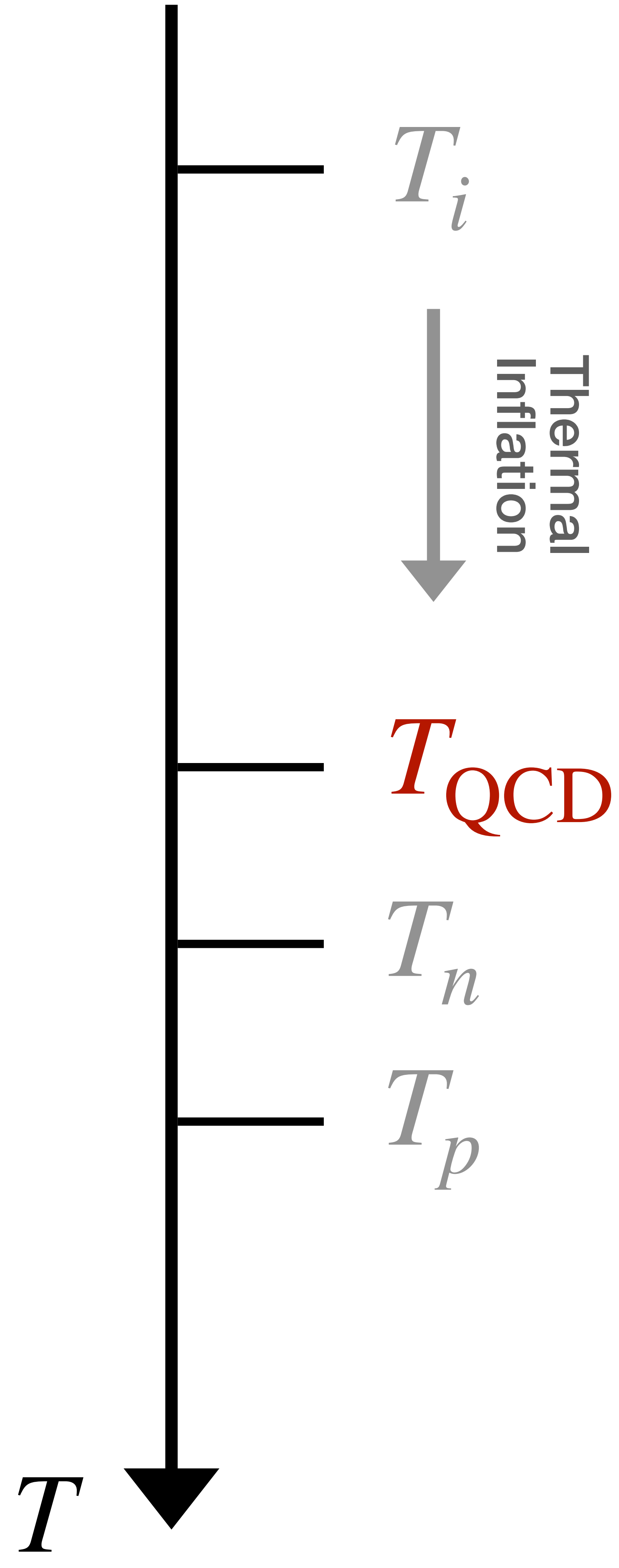
- Thermodynamics fitted against lattice data

  ⟶ Pure Yang-Mills: Polyakov loop extended NJL (PNJL) model

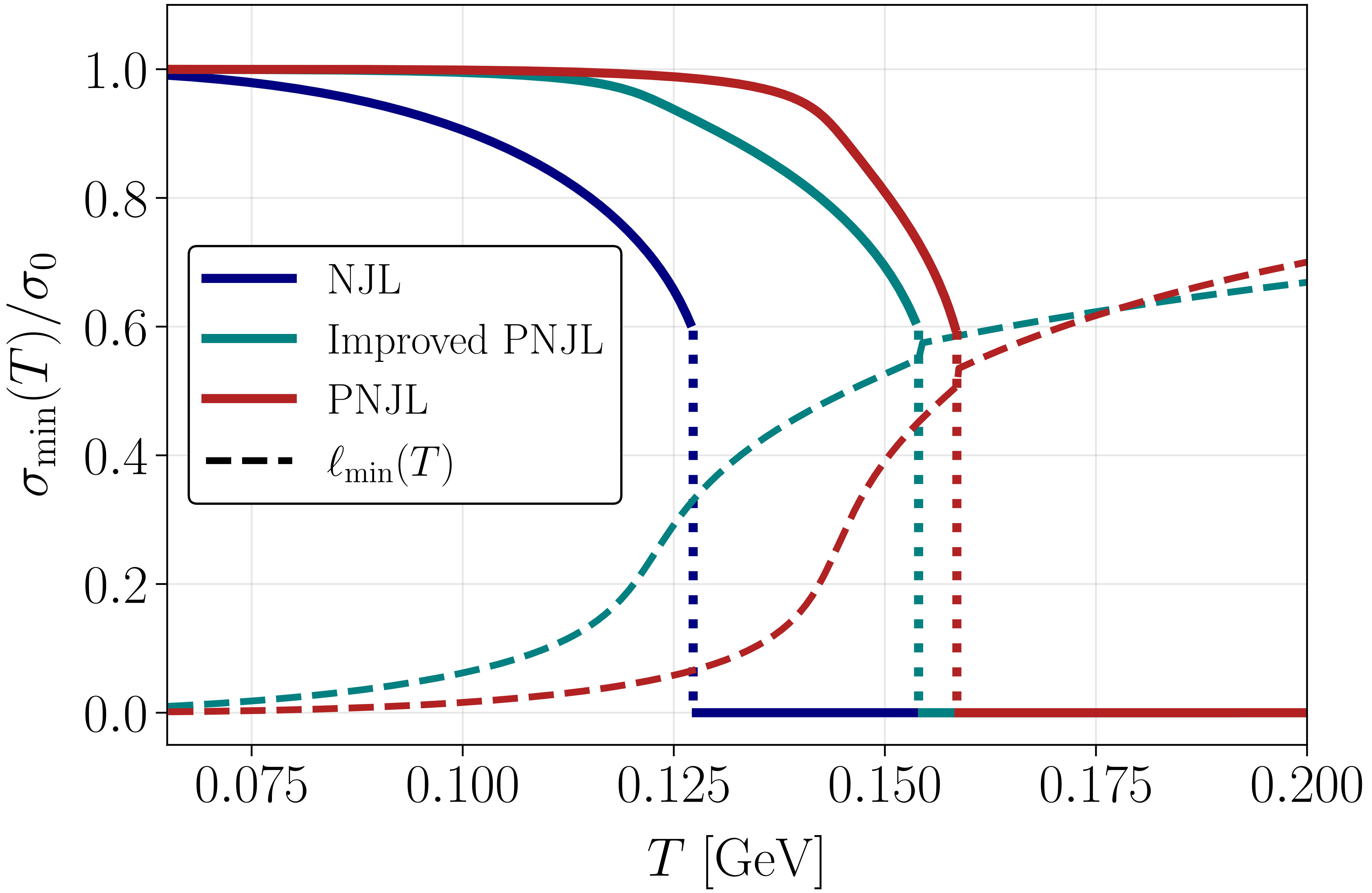
  ⟶ QCD: Improved PNJL model[10]

[9]Fukushima [2004]; Fukushima, Skokov [2017]
[10]Haas, Stiele, Braun et al. [2013]

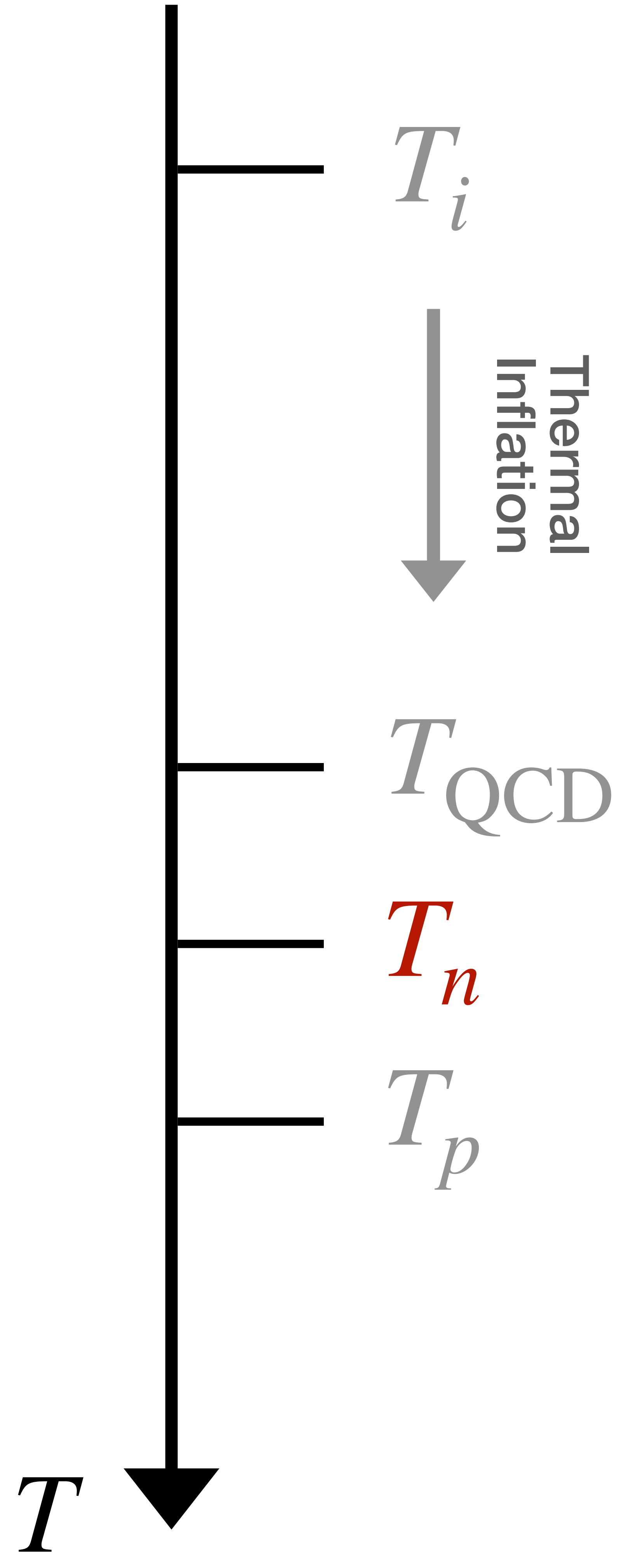
Critical Temperature



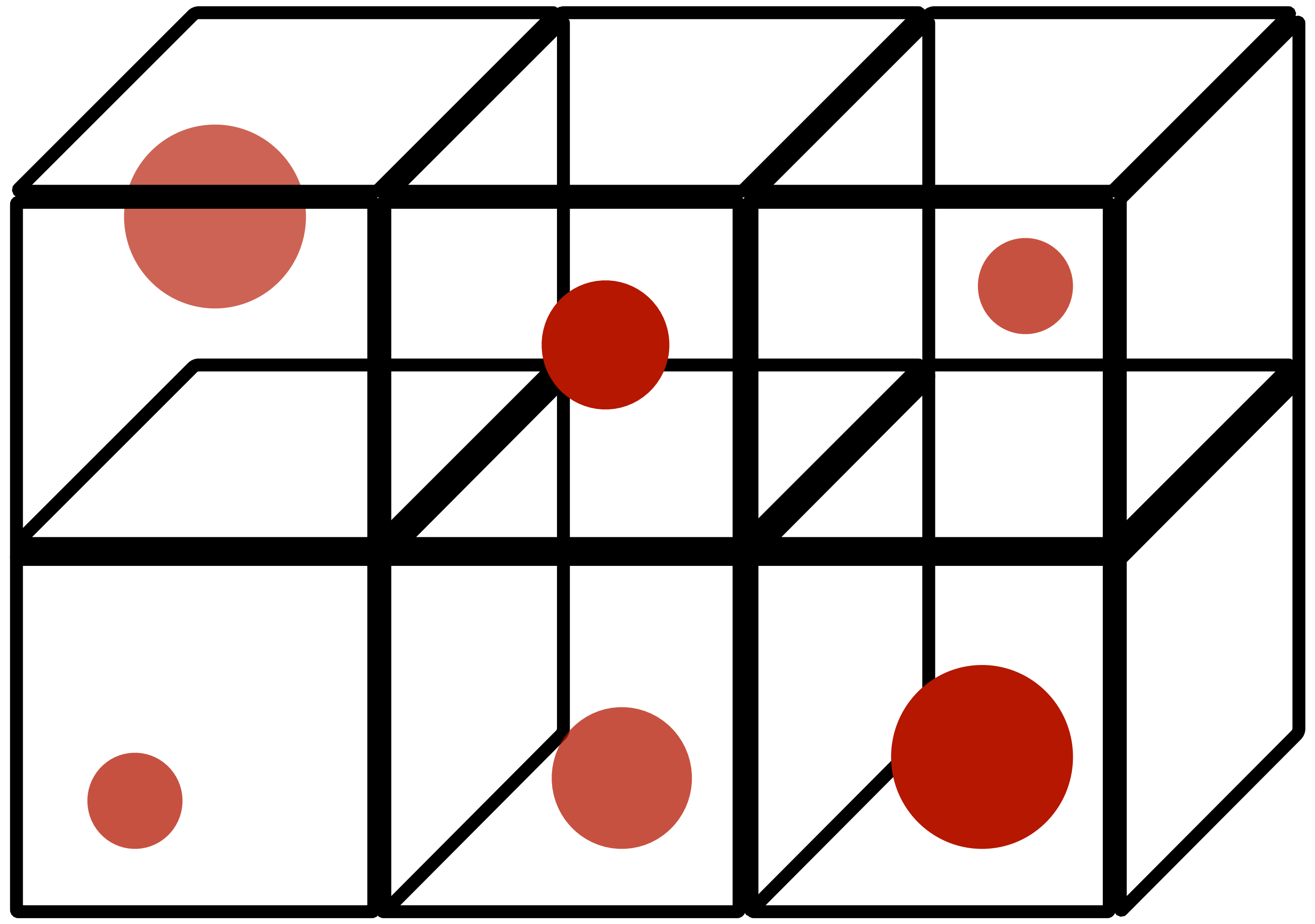
Quark condensation becomes energetically favorable



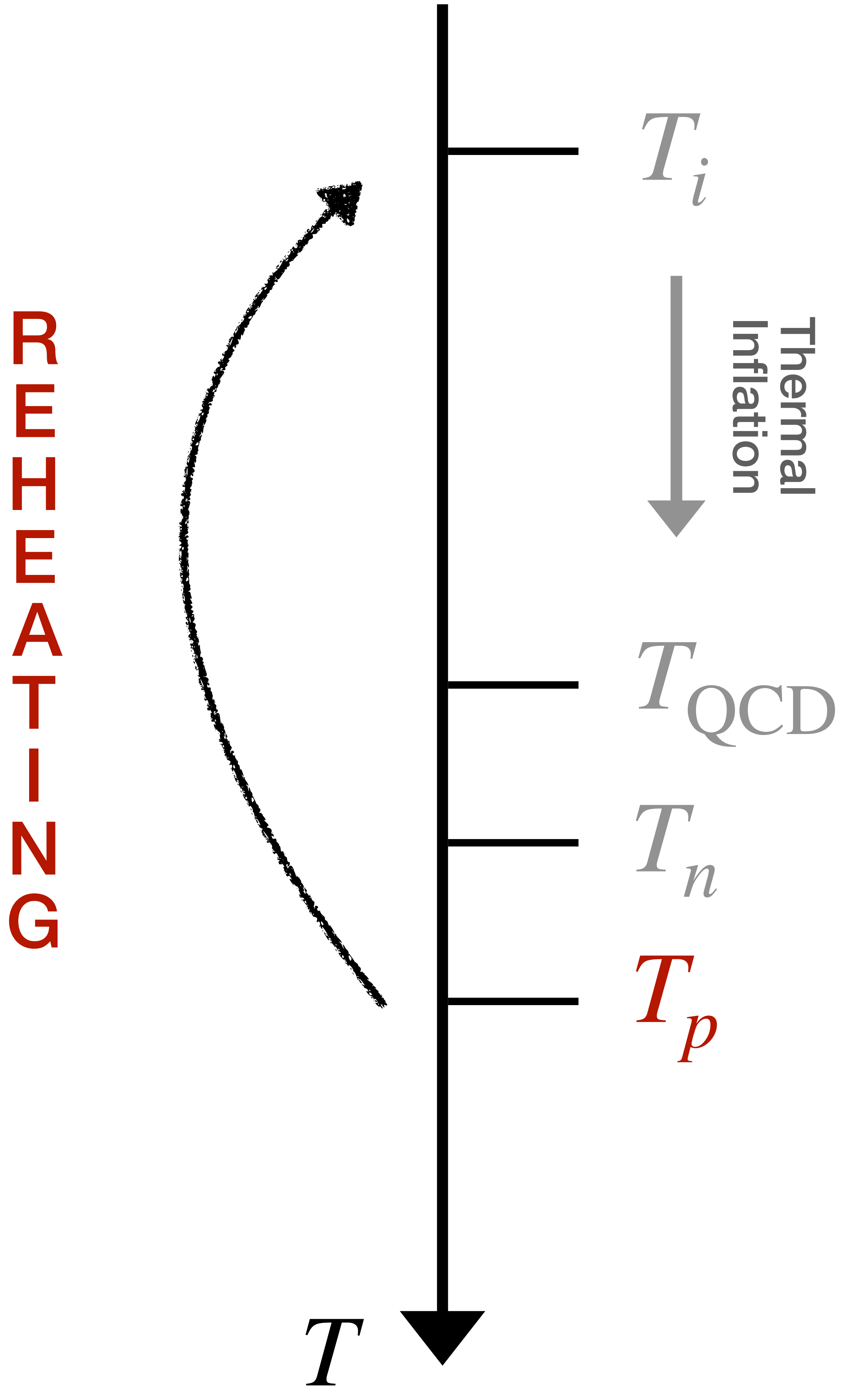
Nucleation Temperature



One hadronic bubble nucleated per Hubble patch

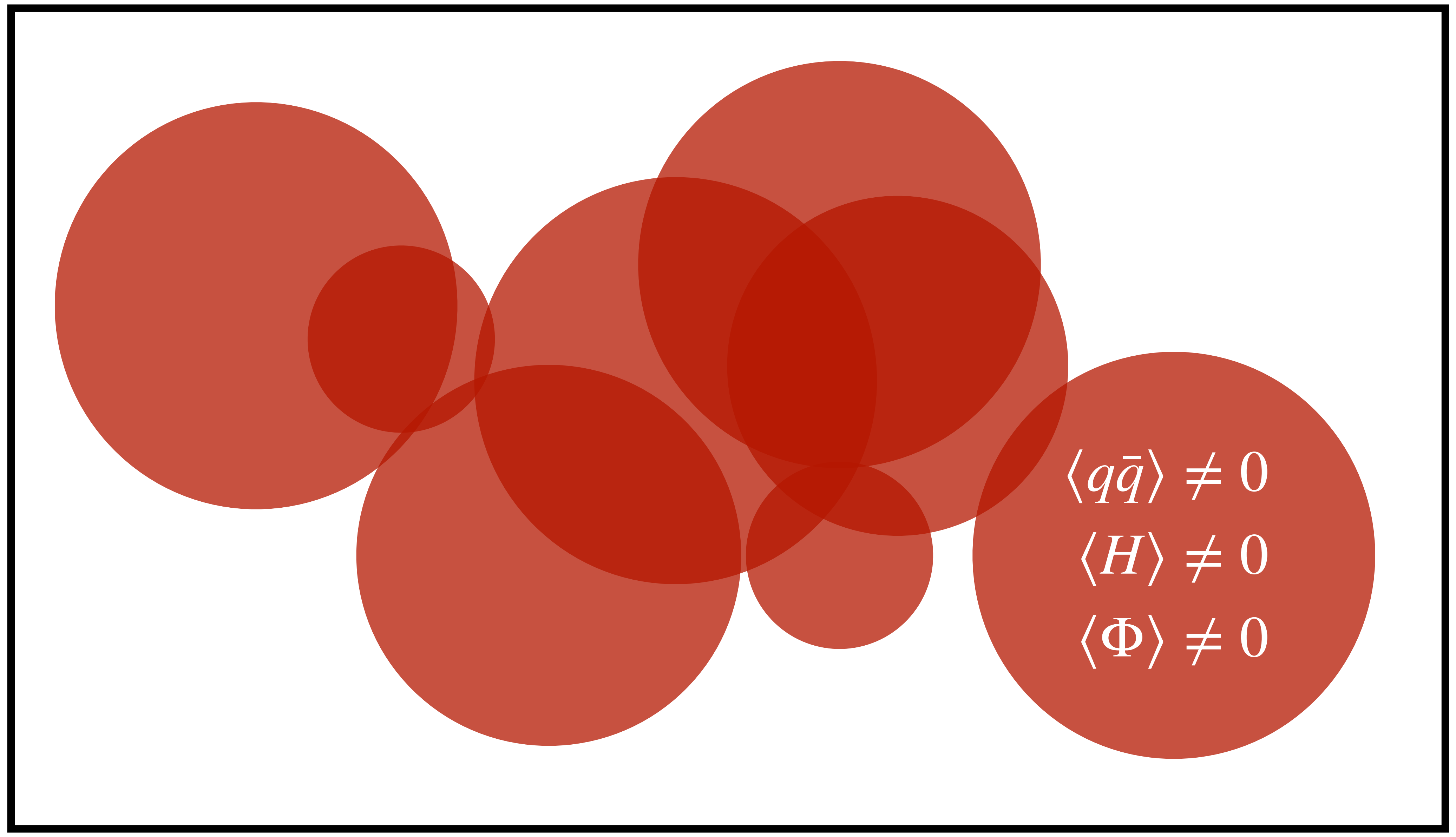


Percolation Temperature



Universe converted into hadronic phase

Exit from supercooling + GW production



Percolation Temperature

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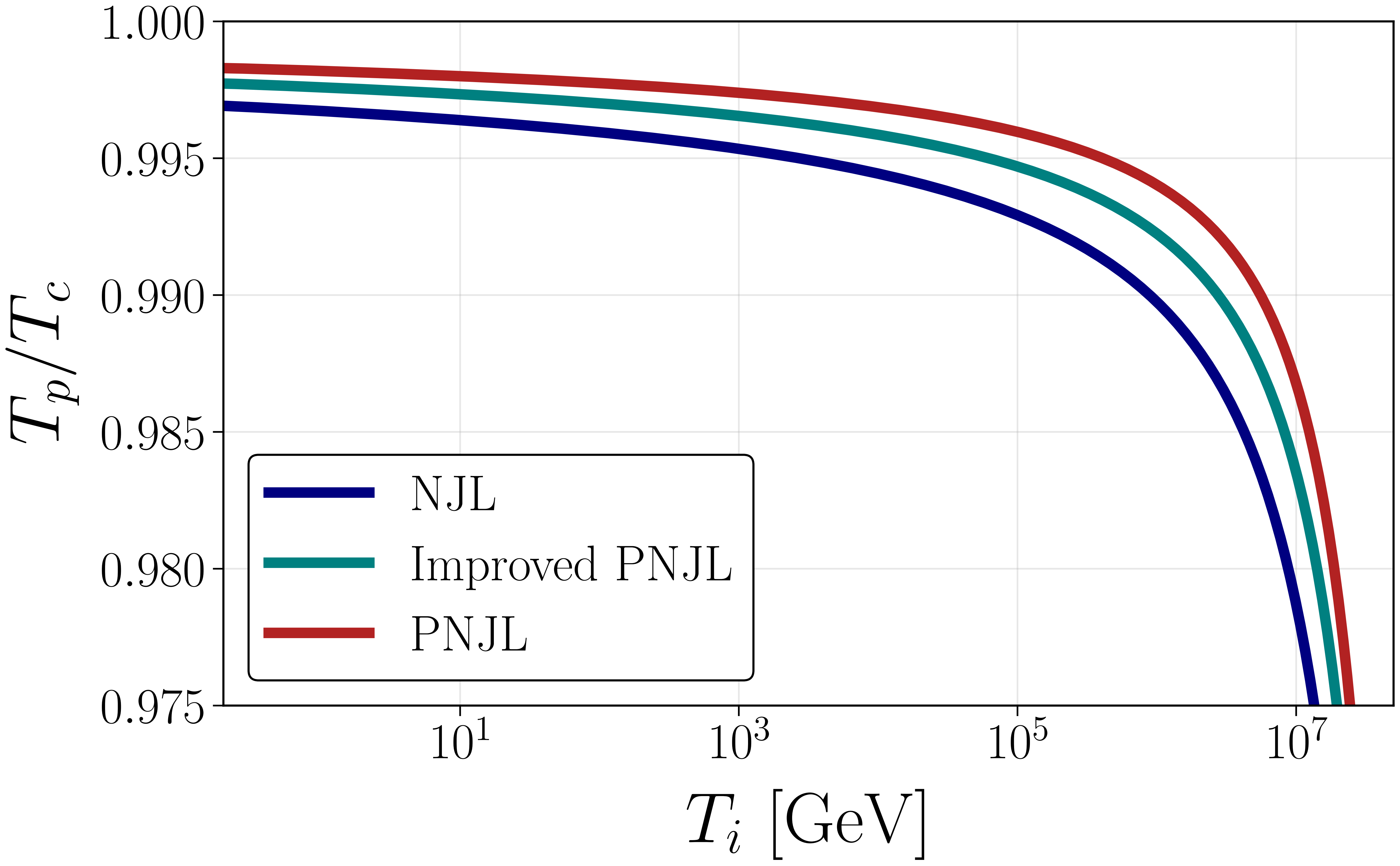
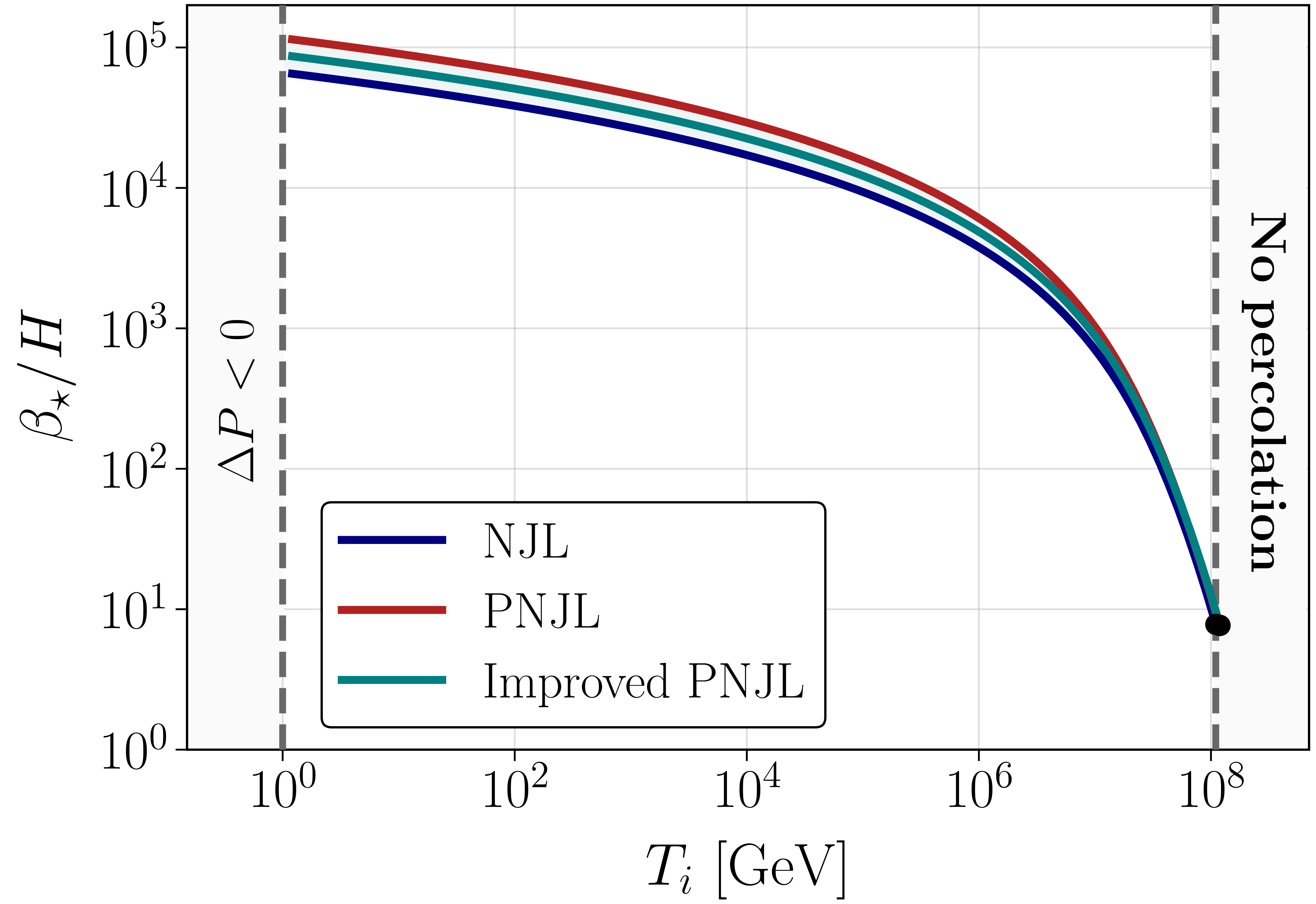
Percolation temperature decreases with increasing amount of supercooling

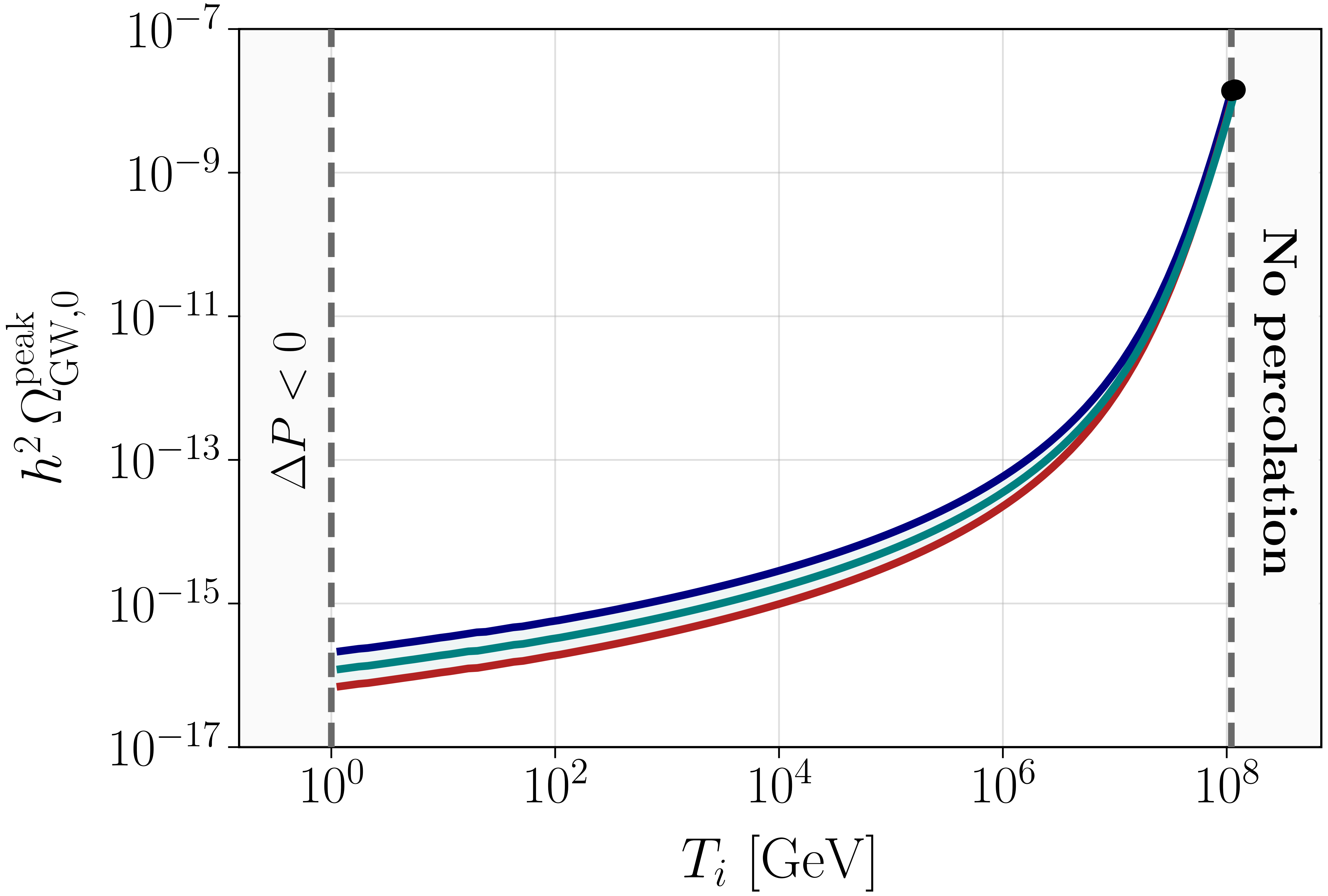


Gravitational Wave Amplitude

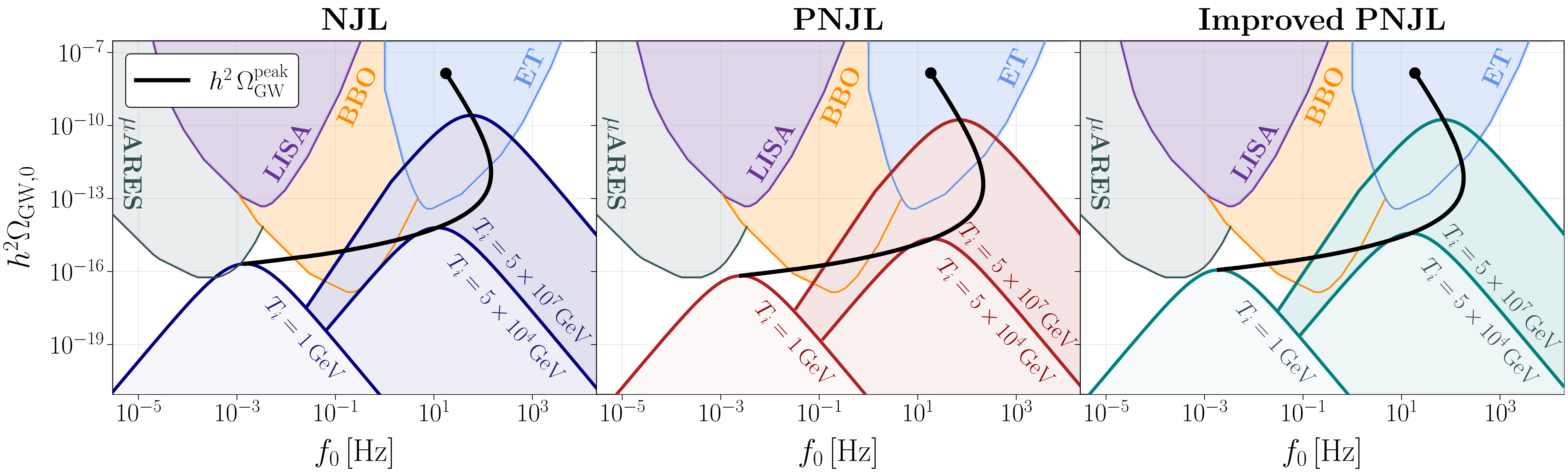
How fast does the PT proceed?

$$\Omega_{\mathrm{GW}} \propto \left(\frac{H}{\beta_\star}\right)^2$$





Observational Prospects



Summary

Classically scale-invariant SM extensions well motivated BSM scenario

Natural outcome: Universe is supercooled down to QCD scale

QCD can trigger the end of thermal inflation

Resulting GW amplitude grows with amount of supercooling

Backup Slides

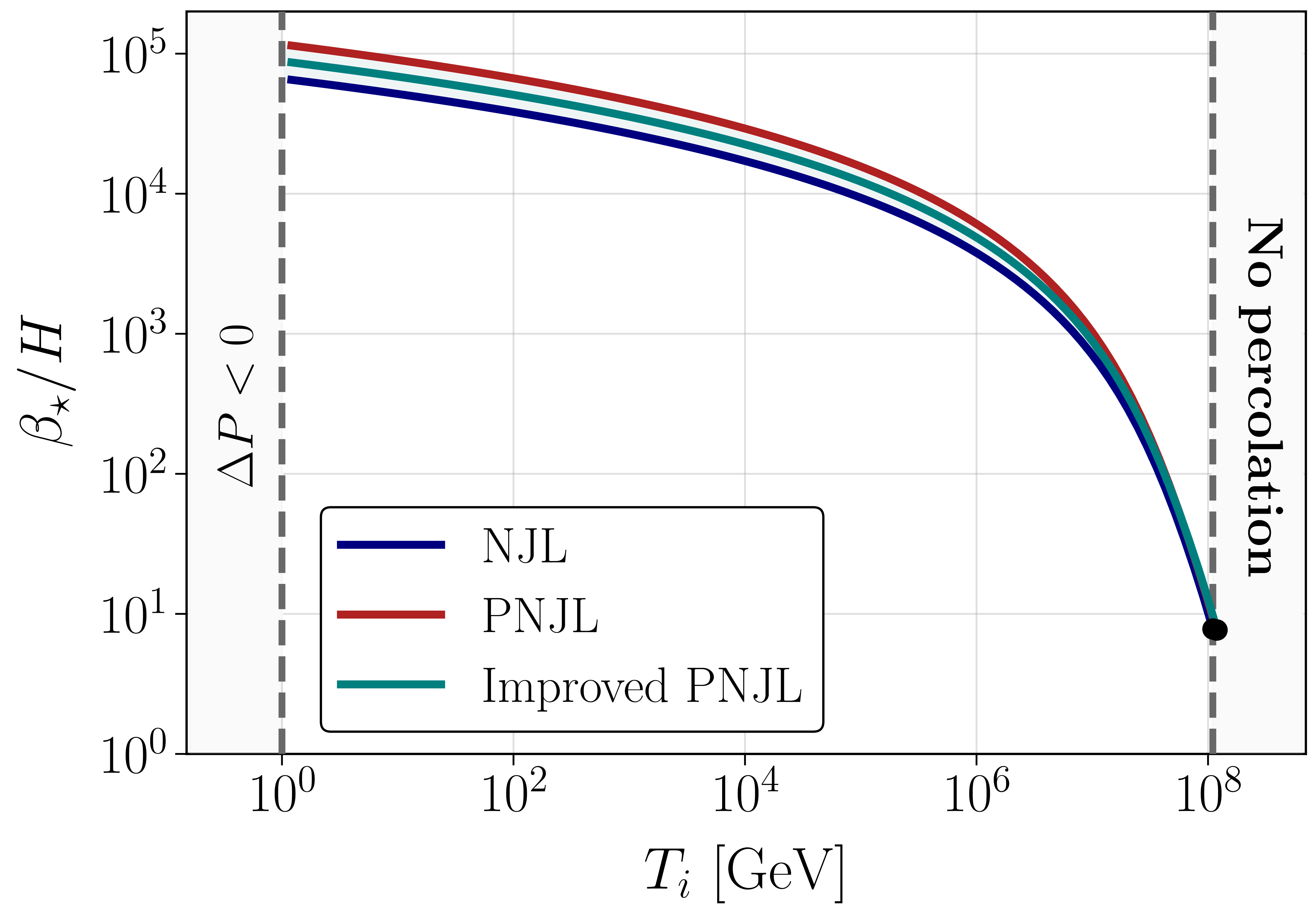
GWs - Frequency Dependence

$$f_0 \propto \beta \frac{a_\star}{a_0} \propto \frac{\beta}{H_\star} H_\star \frac{a_\star}{a_0} \propto \frac{\beta}{H_\star} T_i$$

Large T_i : inverse timescale drops faster than increase in T_i

↓

Frequency decreases again



Temperature Limits

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Minimum Temperature: Consider leading order friction on bubble wall

$$\Delta V = P_{1\to 1} \propto \sum_i \Delta m_i^2 \, T_{\mathrm{QCD}}^2$$

$$\Big\downarrow \; i = \{t, W^{\pm}, Z\}$$

$$\boxed{T_{i,\mathrm{min}} = \mathcal{O}(1)\,\mathrm{GeV}}$$

Temperature Limits

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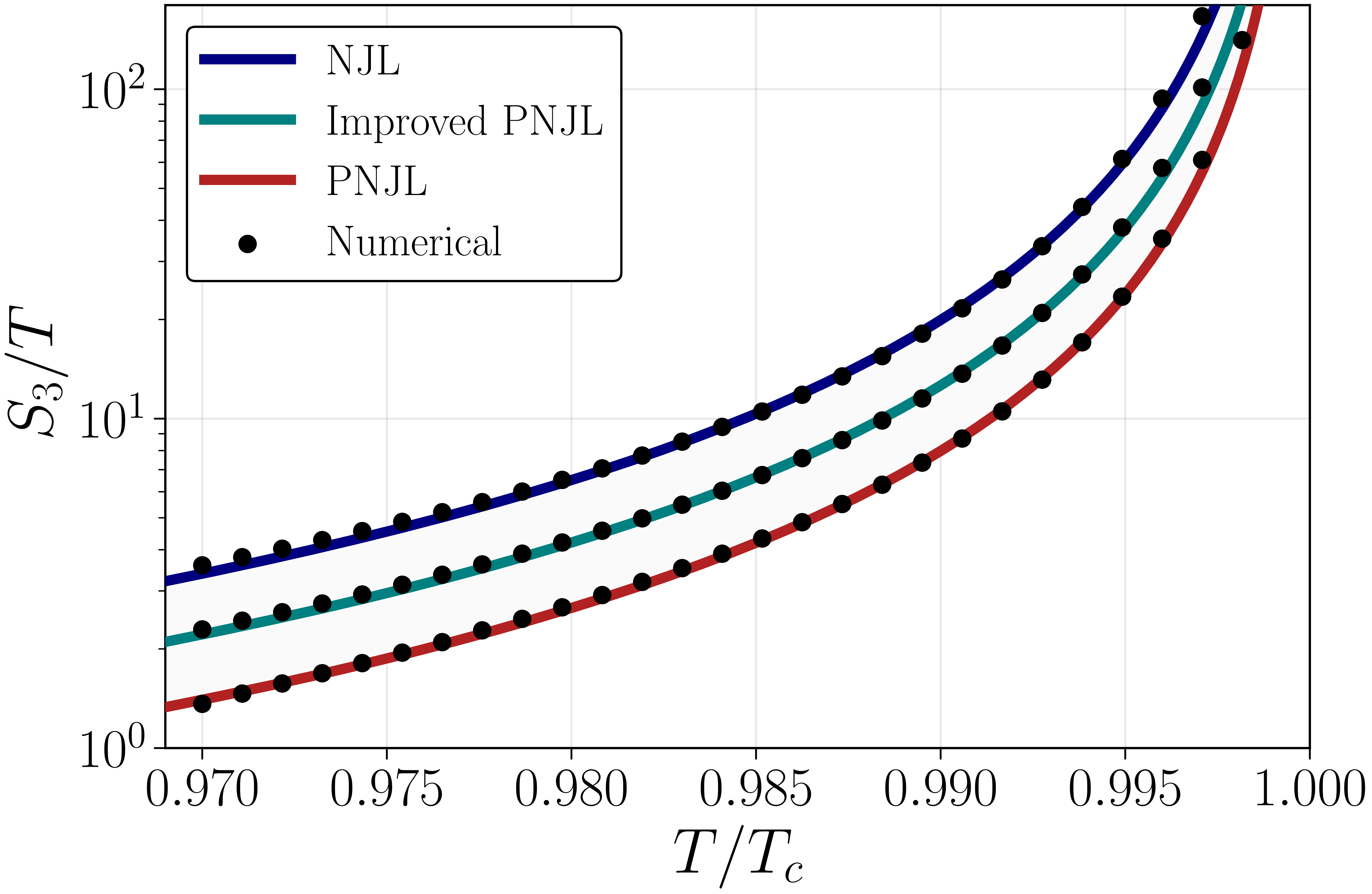
Maximum Temperature: Consider volume trapped in false vacuum

$$\frac{1}{V_{\text{false}}}\frac{dV_{\text{false}}}{dt} = H(T)\left(3 + T\frac{dI(T)}{dT}\right) < 0$$

$$\downarrow$$

$$\boxed{T_{i,\max} = \mathcal{O}(10^8)\,\text{GeV}}$$

Bounce Action



Employ fitting template

$$\frac{S_3}{T} \simeq b\left(1 - \frac{T}{T_c}\right)^{-\gamma}$$

$$\Gamma \propto \exp\left(-\frac{S_3}{T}\right)$$

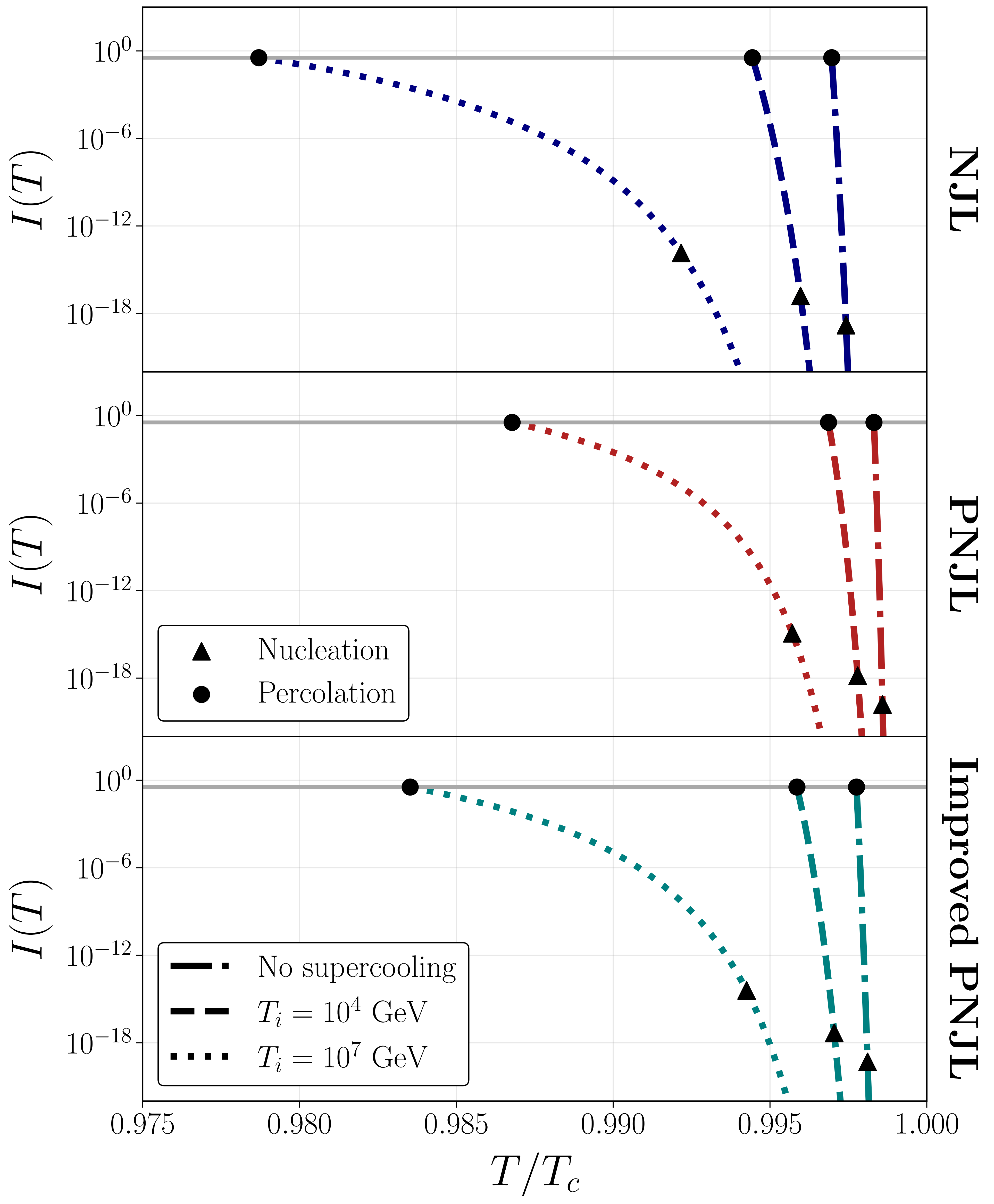
Completing the Phase Transition

Probability to remain in false vacuum

$$P = \exp\left[-I(T)\right]$$

Percolation temperature[11]

$$I(T_p) = 0.34$$



[11] Ellis, Lewicki, No [2018]

Bounce Action

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Solve equation of motion

$$\frac{d^2\sigma}{dr^2} + \frac{2}{r}\frac{d\sigma}{dr} - \frac{1}{2}\frac{\partial \log Z_\sigma}{\partial \sigma}\left(\frac{d\sigma}{dr}\right)^2 = Z_\sigma \frac{dV_{\mathrm{eff}}(\sigma, \ell, T)}{d\sigma}$$

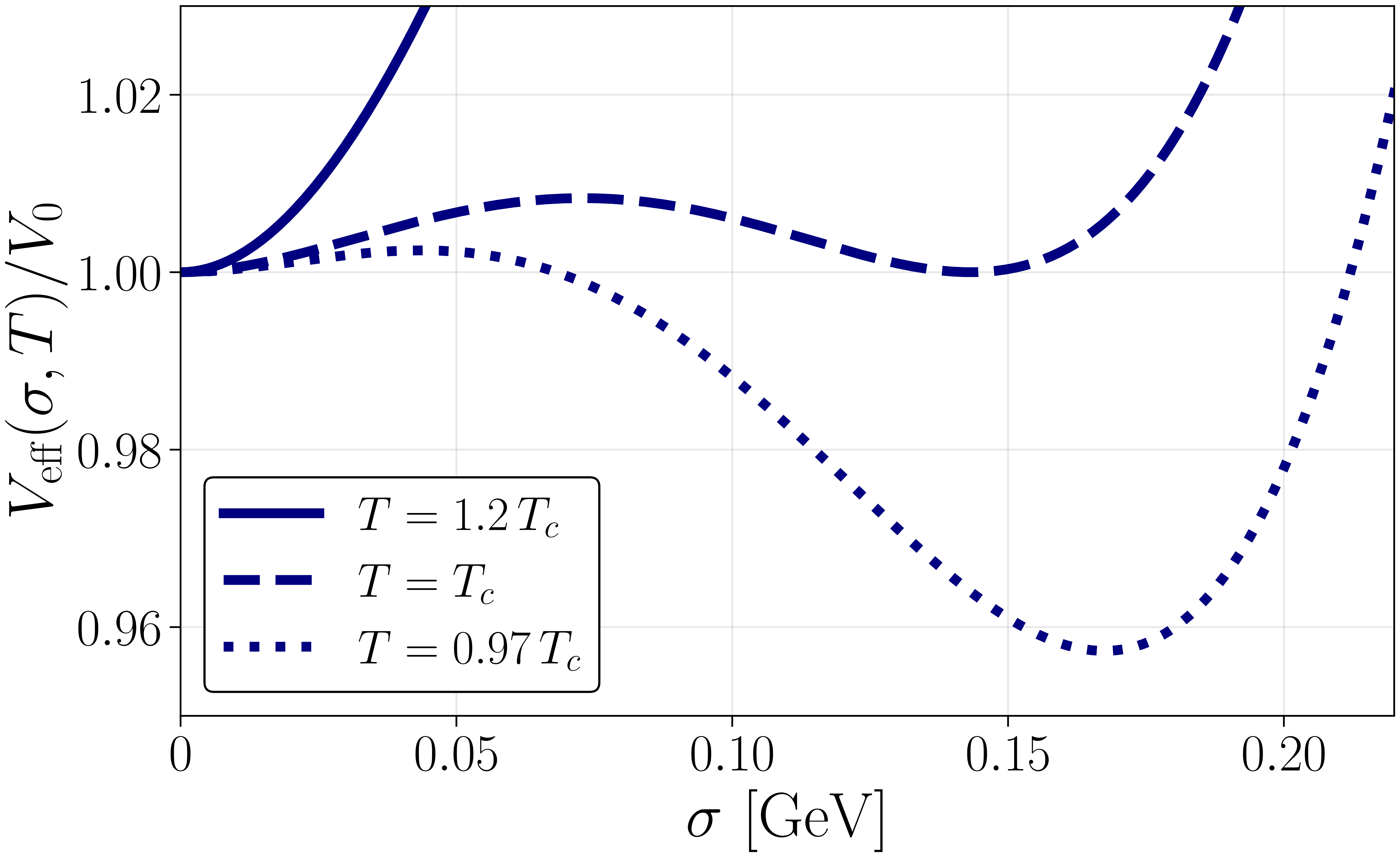
Compute 3D bounce action numerically

$$S_3 = 4\pi \int dr r^2 \left[\frac{Z_\sigma^{-1}}{2}\left(\frac{d\sigma}{dr}\right)^2 + V_{\mathrm{eff}}(\sigma, \ell, T)\right]$$

Z_σ^{-1}: Wave function renormalization

NJL Effective Potential

$$V_{\text{eff}}(\sigma, T) = V_0(\sigma) + V_1(\sigma) + V_T(\sigma, T)$$



Transition Timescale - 4D Cutoff

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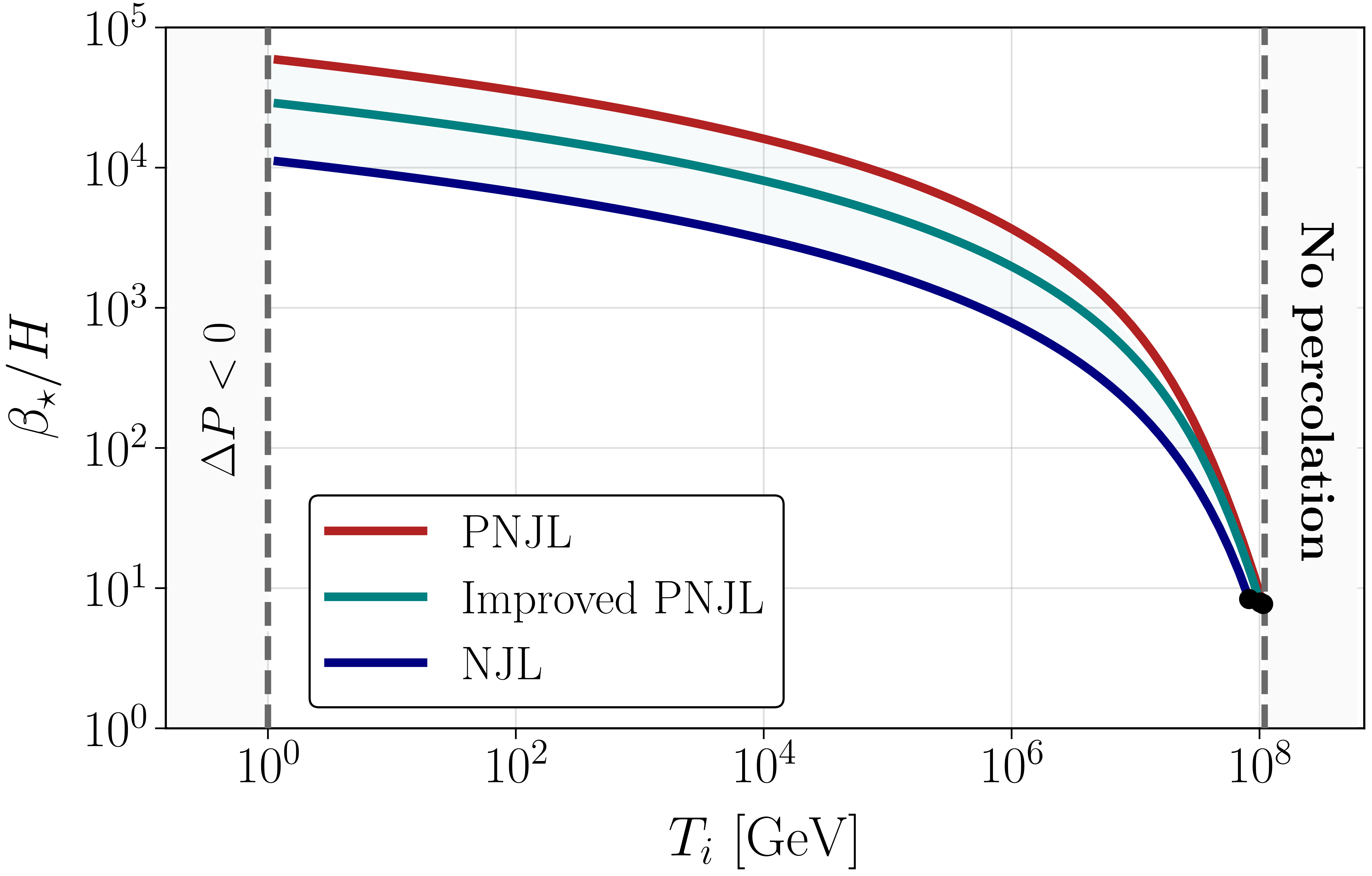

Cutoff Scheme Dependence

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